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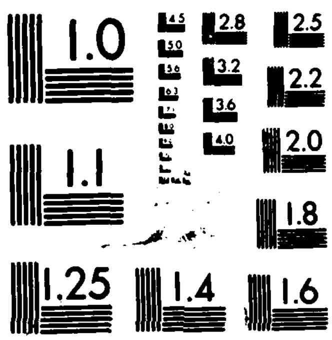
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Annual Scientific Report

on

ADVANCED DIAGNOSTICS FOR REACTING FLOWS

Contract F49620-83-K-0004

Prepared for

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For the Period

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Submitted by

R. K. Hanson, Principal Investigator

HIGH TEMPERATURE GASDYNAMICS LABORATORY
Mechanical Engineering Department
Stanford University

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19. ABSTRACT (Continue on reverse if necessary and identify by block number)

Progress is reported for the past year of an interdisciplinary program to innovate modern diagnostic techniques applicable to combustion and plasma flows. Research topics include: (1) digital flowfield imaging, including temporally and spatially resolved species and temperature imaging using planar laser-induced fluorescence (PLIF); (2) quantitative particle imaging in spray flames using planar Mie scattering (PMS); (3) quantitative velocity and pressure imaging using variations of PLIF; (4) advanced solid-state camera/computer systems for high-speed and high-resolution recording, processing and display of flow image data; (5) fiber optic absorption/fluorescence sensors employing tunable UV, visible and IR laser sources for species measurements; (6) laser wavelength modulation spectroscopy, using rapid-scanning UV, visible and IR laser sources, for absorption and fluorescence measurements of species, temperature and absorption lineshapes; (7) plasma diagnostics utilizing laser-induced fluorescence and wavelength modulation techniques; (8) laser interactions with plasmas and combustion gases; and (9) investigation of other new diagnostic concepts.

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1.0 INTRODUCTION

Progress is reported for the past year of an interdisciplinary program to innovate modern diagnostic techniques applicable to combustion and plasma flows. Research topics include: (1) digital flowfield imaging, including temporally and spatially resolved species and temperature imaging using planar laser-induced fluorescence (PLIF); (2) quantitative particle imaging in spray flames using planar Mie scattering (PMS); (3) quantitative velocity and pressure imaging using variations of PLIF; (4) advanced solid-state camera/computer systems for high-speed and high-resolution recording, processing and display of flow image data; (5) fiber optic absorption/fluorescence sensors employing tunable UV, visible and IR laser sources for species measurements; (6) laser wavelength modulation spectroscopy, using rapid-scanning UV, visible and IR laser sources, for absorption and fluorescence measurements of species, temperature and absorption lineshapes; (7) plasma diagnostics utilizing laser-induced fluorescence and wavelength modulation techniques; (8) laser interactions with plasmas and combustion gases; and (9) investigation of other new diagnostic concepts.

2.0 PROJECT SUMMARIES

Included in this section are summaries of progress in each of seven project areas. In most cases, each project summary contains the following subsections: (a) Introduction; (b) Scientific Merit; (c) Status Report; (d) Publications and Presentations; (e) Personnel. Additional descriptions of this work may be found in the cited publications and in our previous annual scientific reports.

2.1 Digital Flowfield Imaging

Introduction

The utility of flow visualization as a diagnostic in studies of fluid mechanics and combustion is well established. Until recently, however, most visualization techniques have been qualitative and based on line-of-sight approaches poorly suited for flows with three-dimensional characteristics. With the recent development of laser-based light scattering techniques, it has become possible to obtain spatially and temporally resolved quantitative records of flow properties throughout a plane (and ultimately throughout a volume) using sheet illumination and a scattering technique such as Raman, fluorescence or Mie scattering. Such multipoint measurements essentially provide "images" of the flowfield property being monitored; as these images can be recorded on modern solid-state array detectors, coupled to a computer for analysis and display, we call this approach "Digital Flowfield Imaging." Work along these lines is now in progress at Stanford, Yale, SRI, Sandia (Livermore) and the Aeropropulsion Lab at Wright Field. As examples of the capability of these new methods, in our laboratory at Stanford we have made instantaneous (8 nsec), multiple-point (10^4 points) measurements of several species (OH, NO, O_2, CH, C_2 and Na) in a variety of laboratory flames using planar laser-induced fluorescence (PLIF), and we have recently initiated work to provide simultaneous particle size and spacing measurements in spray flames using planar (PMS). The sensitivity demonstrated thus far for molecular species is in the 10's of ppm range, with spatial resolution typically much better than 1 mm. Of equal importance, we have recently demonstrated a variation of PLIF which

yields temperature, and another variation which should enable simultaneous measurements of pressure and velocity (see Section 2.2) without particle seeding. These new techniques provide significant advances in measurement capability with potential scientific impact extending well beyond the field of combustion for which the methods were originally developed.

Scientific Merit

Digital flowfield imaging has the potential to stimulate significant scientific advances in several fields, including fluid mechanics, combustion and plasma sciences. Our research also contributes to the advancement of related technologies, such as lasers and image processing, and it adds to the fundamental data bases for spectroscopy and reaction kinetics of high temperature gases and plasmas. The Stanford program has made unique, pioneering contributions to flowfield imaging, particularly with regard to conceiving and demonstrating new sensing strategies for the flowfield quantities of interest, and in designing and implementing new intensified camera systems which incorporate recent advances in intensifiers and array detectors interfaced with laboratory microcomputers.

Status Report

Our work on flowfield imaging has been detailed in a series of papers and reports (see list at end of this section), and so here we focus only on recent activities. For convenience and clarity we provide separate status reports on: Species Imaging, Temperature Imaging, Spray Flame Imaging, and System Improvements.

(a) Species Imaging

Previously we have applied PLIF to visualize OH, Na, NO and I_2 in several flows. Recently we have worked to develop measurement capability for O_2, C_2 and CH, as we discuss briefly below. Molecular oxygen is a critical species in many combustion studies, but is usually considered to be inaccessible by optical techniques as it absorbs strongly only in

the UV below 200 nm. In addition, fluorescence is known to be weak owing to strong predissociation effects. Two factors may mitigate this conventional viewpoint: (1) the recent development of high energy, tunable UV and VUV laser sources, particularly excimer and Raman-shifted excimer lasers; and (2) the fact that the absorption transitions of interest in characterizing high temperature gas systems may be much stronger than the (separate) transitions appropriate for monitoring O_2 at atmospheric conditions.

Over the past year we performed a literature survey to familiarize ourselves with relevant past work, and we developed computer codes to allow prediction of O_2 absorption and fluorescence spectra as a function of temperature and of excitation wavelength. The calculations are complex and will not be described here, but in summary we found that either an ArF excimer laser at 193 nm or Raman-shifted ArF at 179 nm should be well suited for detecting O_2 over a range of temperatures. Subsequently, we moved to the laboratory and are now ready to report our initial results. Figure 1 provides a sample instantaneous (10 nsec) O_2 image obtained in a fuel-rich CH_4/air flame. We believe this is the first digital image of O_2 obtained by any method in any flowfield. Owing to the broad importance of O_2 in aerodynamics and combustion, we regard this as a particularly important accomplishment. Further work to improve this technique is in progress, and at the same time we are investigating, by computer calculations with our O_2 spectroscopy program, candidate schemes for visualizing temperature, pressure and velocity based on O_2 fluorescence.

Our interest in imaging CH and C_2 stems from their potential for in monitoring the instantaneous flame position and thickness in gaseous diffusion flames and in burning fuel sprays. The status of the work is that we have just obtained our first 2-D images of CH and C_2 in a variety of gaseous and spray flames. The work is being written up for presentation at the forthcoming Western States combustion meeting.

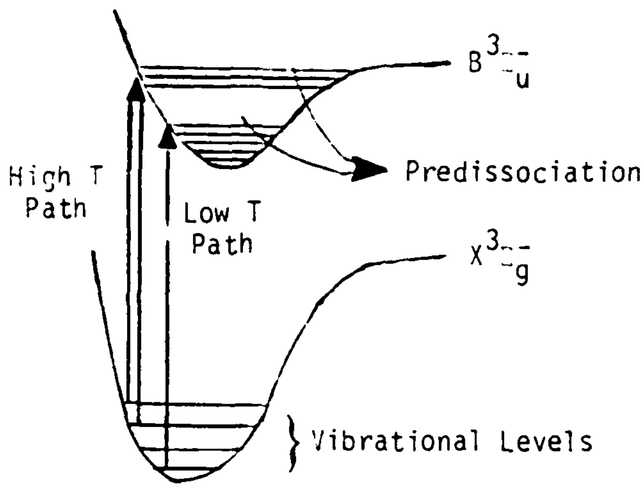
(b) Temperature Imaging

Temperature is a parameter of obvious importance in characterizing reacting flowfields, and hence a scheme for quantitative imaging of

ACHIEVEMENT

DIGITAL FLUORESCENCE IMAGING OF O_2 IN COMBUSTION FLOWS

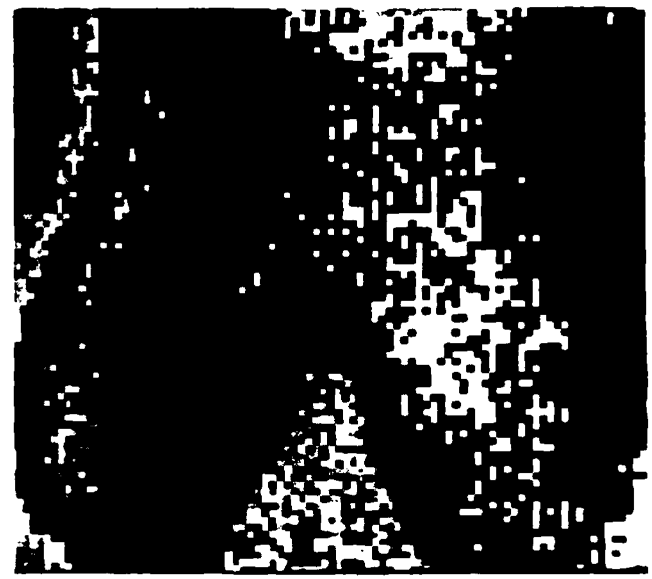
- EXCIMER LASER PROVIDES ACCESS TO UV TRANSITIONS OF O_2



SHEET EXCITATION
(PULSED ArF LASER)

λ = 193 nm, τ = 17 nsec

BROADBAND DETECTION
100 x 100
INTENSIFIED ARRAY



Digital Fluorescence Image of O_2
Fuel-Rich CH_4/Air Flame

- FIRST 2-D FLUORESCENCE IMAGE OF O_2
- USE OF HIGH-TEMPERATURE TRANSITIONS INCREASES SIGNAL BY ORDERS OF MAGNITUDE
- USE OF PREDISSOCIATED TRANSITIONS ELIMINATES PROBLEM WITH FLUORESCENCE YIELD DEPENDENCE ON PRESSURE AND SPECIES
- USE OF HIGH-REPETITION RATE EXCIMER LASER ENABLES STUDIES OF FLAME DYNAMICS

Fig. 1 Approach and results for digital imaging of O_2.

Hanson, Lee & Paul/Stanford U.

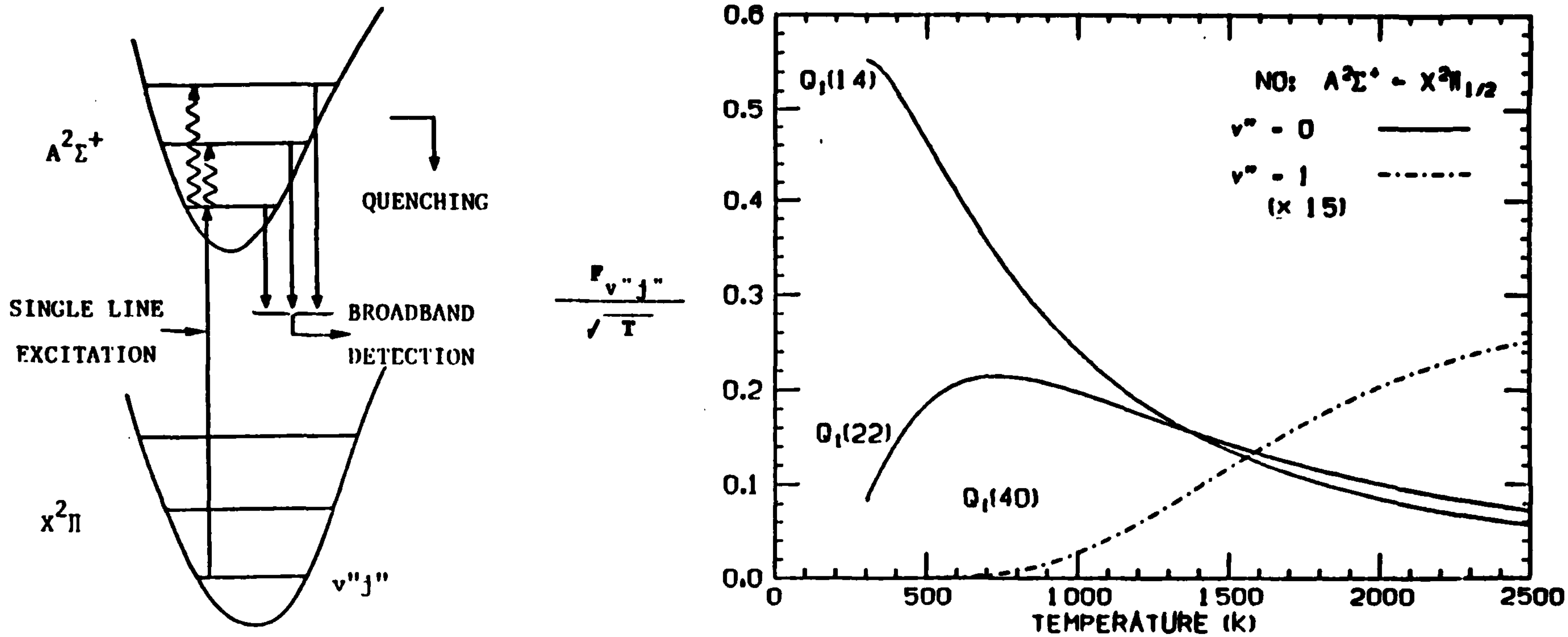
temperature would have broad application in combustion and plasma-related research. An ideal temperature visualization scheme would be sensitive, easy to calibrate, and would involve, for simplicity, only a single laser source. Although laser-induced fluorescence has been demonstrated for single-point temperature measurements, and very recently (by Svanberg et al., in Sweden, and Cattolica, at Sandia) for multiple-point measurements, these workers have employed two laser sources and, as a result, were only able to work in steady flames. Here we report a PLIF scheme which offers several advantages, including the use of only one laser source.

The strategy which we employ is to seed the flow uniformly with a non-reactive tracer species such as NO. Assuming linear (non-saturated) excitation using a spectrally broad (greater than the absorption linewidth) pump laser, with broadband fluorescence detection and a uniform laser intensity distribution, the fluorescence intensity emanating from a point in the flowfield is given simply by

$$I_F = C\, n_i\, f_{vj}\, A/(A + Q) = C\, X_i\, f_{vj}/\sqrt{T} \qquad (1)$$

where C represents a group of known quantities, n_i is the number density of the absorber i, f_{vj} is the temperature-dependent Boltzmann fraction in the absorbing state (v,j), and A/A+Q is the photon yield (fraction of absorbed photons re-emitted into the detection bandwidth). For present purposes we assume that the Einstein coefficient for spontaneous emission, A, is much smaller than the electronic quench rate, Q, and that Q may be represented by $n\sigma\bar{v}$, where n is the total number density, σ is an effective cross-section and $\bar{v}$ is the mean molecular speed proportional to $T^{1/2}$; thus $A/A+Q \simeq A/n\sigma\bar{v}$. Under conditions where σ may be regarded as a constant, and using the symbol X_i for the mole fraction of i (i.e., n_i/n), we obtain Eq. (1). Thus if the mole fraction of i is fixed the fluorescence intensity I_F is a known function of temperature alone.

This approach for temperature visualization (see Fig. 2) has the important advantage of requiring a single excitation wavelength (and



FLUORESCENCE EQUATION → $S \sim N_{NO} \times F_{v"j"} \times \frac{A}{A + Q}$

ASSUMPTIONS → $A << Q \; , \; Q = N \sigma \bar{v}, \; \bar{v} \sim \sqrt{T}$

RESULT → $S \sim [N_{NO}/N] \times [F_{v"j"} / \sqrt{T}]$

Fig. 2. Excitation/detection scheme for temperature visualization and plot of fluorescence signal (S) sensitivity to temperature for three transitions.

hence a single laser). The sensitivity of the fluorescence signal to temperature depends on the quantity $f_{vj}/\sqrt{T}$, and hence the lower level quantum states v,j (vibration, rotation) may be chosen to optimize the signal in the temperature region of interest. Calibration may be achieved simply if the temperature is known at any flowfield point or region. Alternatively, if the function $f_{vj}/\sqrt{T}$ has a peak value within the temperature range present in the flowfield, then the calibration factor follows directly from the maximum signal observed. This method is limited, however, to flowfields where the double-valued nature of $f_{vj}/\sqrt{T}$ versus T introduces no ambiguity. In general, corrections are needed to account for nonuniform laser illumination, nonuniform pixel responsivity and background light levels.

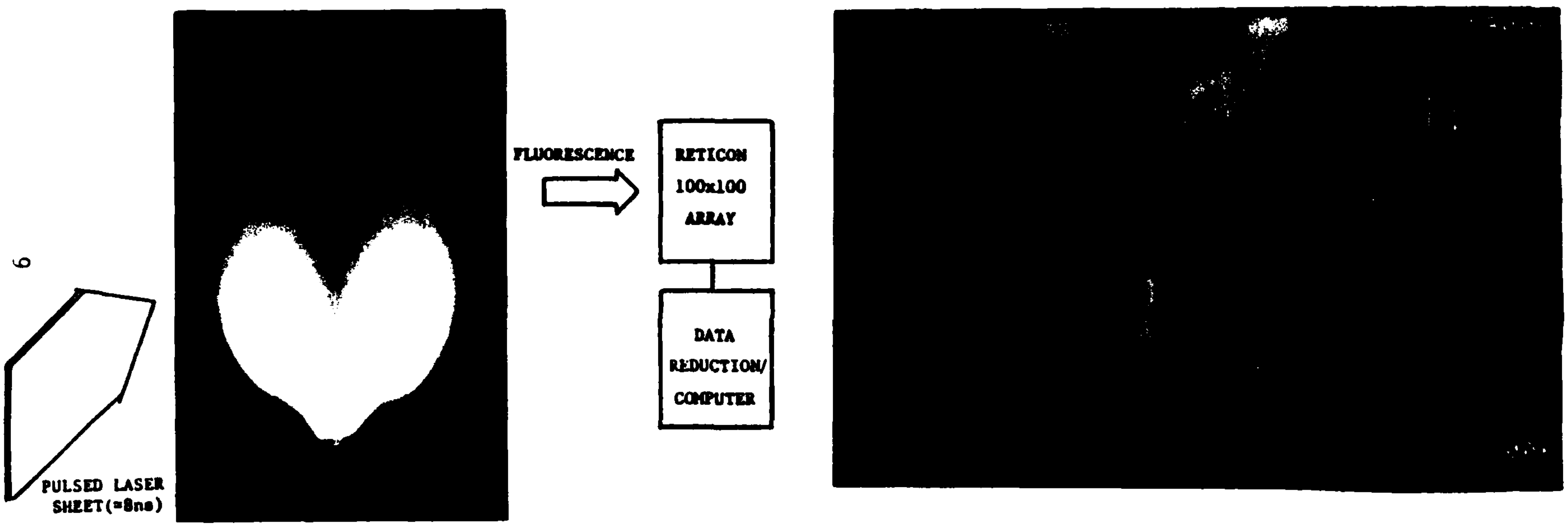
A sample result showing the temperature contours obtained with a single laser shot (8 nsec) in a rod-stabilized flame is presented in Fig. 3. Here premixed CH_4 and air at atmospheric pressure flow vertically over a 1.5 mm diameter horizontal rod, resulting in a roughly V-shaped flame stabilized by the rod. The fuel lean (equivalence ratio $\approx$ 0.6) mixture is seeded with approximately 2000 ppm of NO, which may be regarded as non-reactive for these conditions. A vertical sheet (3 cm x 0.2 mm) of laser light near λ = 225.6 nm, produced by mixing the frequency-doubled output of a Nd:YAG-pumped dye laser with the residual 1.06 μm beam, is used to excite a single line in the $A^2\Sigma^+(v=0) \leftarrow X^2\Pi_{1/2}(v=0)$ NO band. The digital images of the fluorescence intensity, emanating from a 10 mm x 10 mm region, were processed to yield the temperature contours shown in Fig. 3. For this case, obtained using the $Q_1(22)$ line which has a peak in the function $f_{vj}/\sqrt{T}$ at 740K, the calibration was achieved by searching for the maximum signal (present on both sides of the rod) and setting the temperature at these locations at 740K. Again, use of different v,j states allows some flexibility in emphasizing different temperature regimes.

The work described above has recently been published (see publication 12 in the list at the end of this section). Current work with temperature imaging is directed toward refining the experimental set-up and procedures for this constant mole fraction approach, extending its

APPROACH

2-D TEMPERATURE MEASUREMENT

- LASER INDUCED FLUORESCENCE YIELDS INSTANTANEOUS 2-D TEMPERATURE FIELDS



- FIRST TECHNIQUE FOR INSTANTANEOUS 2-D TEMPERATURE MEASUREMENTS
- NOVEL SINGLE-WAVELENGTH TECHNIQUE CAN BE SELF-CALIBRATING
- POTENTIAL APPLICATION TO UNSTEADY REACTING AND NONREACTING FLOWS

Fig. 3. Approach and results for temperature visualization technique.

Hanson & Seitzman/Stanford Univ.

application to other flows, and also to investigating the sensitivity of the NO quench rate to combustion gas composition at high temperatures.

(c) Spray Flame Imaging

During the past year we initiated work to establish PLIF and planar Mie scattering (PMS) techniques in evaporating and burning fuel sprays. We regard this combined development of PLIF and PMS as a logical extension of our past effort on digital flow imaging. Further, the development of such capability for measurements in two-phase flows is critical for studies in practical combustors and for fundamental research on droplet and solid propellant combustion. This work is jointly sponsored by AFOSR and ONR.

Thus far we have: (1) completed assembly of a small-scale spray combustion facility; (2) set up a laser sheet illumination arrangement and made preliminary photographic and digital imaging measurements of Mie scattering to characterize our spray flame; (3) performed Mie scattering calculations to aid in the interpretation of the PMS measurements; and (4) performed initial imaging experiments of OH, CH and C_2 in the spray burner facility.

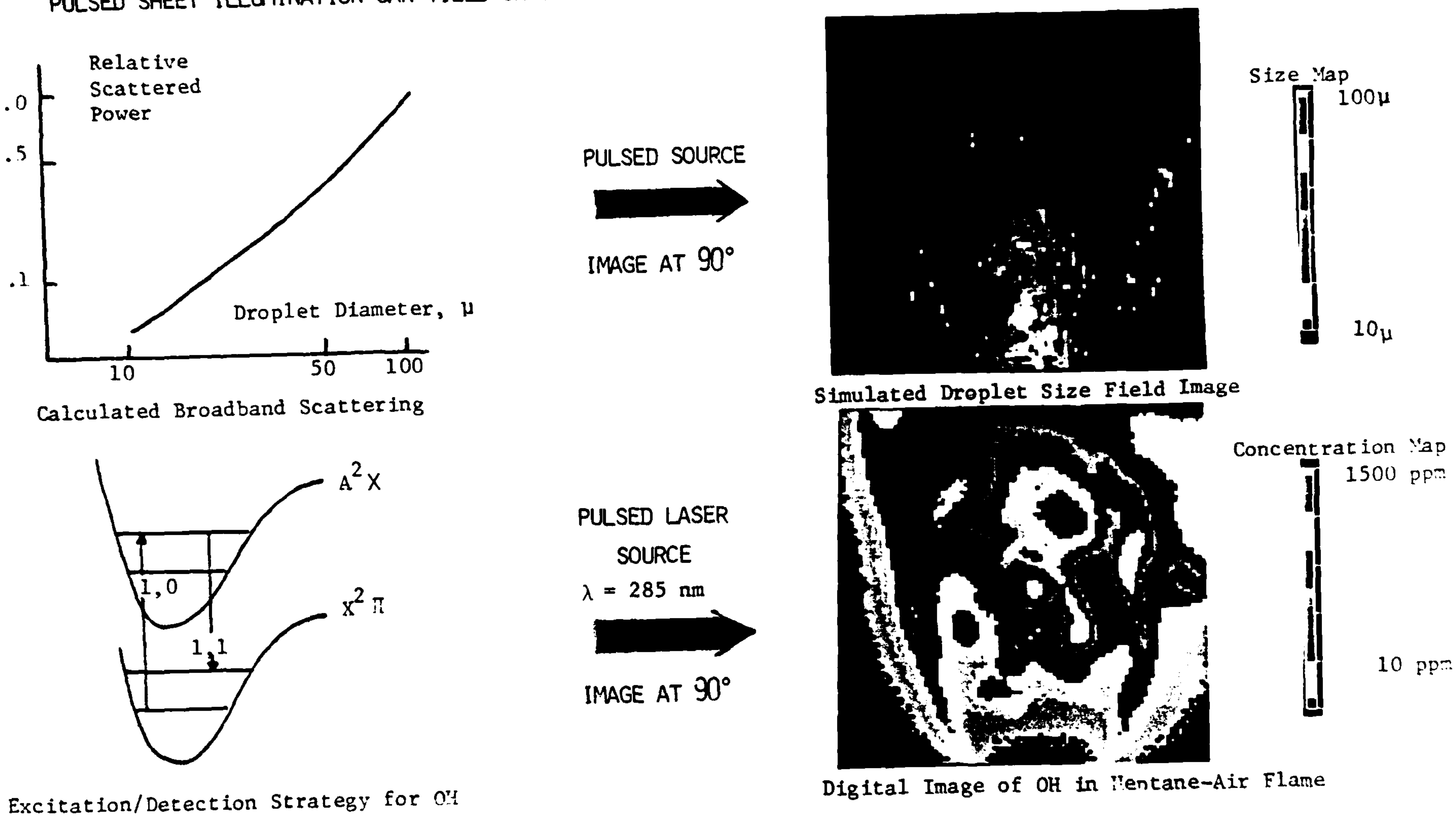
A schematic diagram of the approach and some representative PMS and PLIF results for a burning spray are shown in Fig. 4. The fuel was n-heptane, flowing at a rate of about 0.2 gallons/hr from an air-atomizing siphon nozzle (Delevan), and the size of the region imaged was about 8 cm x 8 cm. In addition to the OH image shown, we also have obtained image data for CH and C_2. To our knowledge, these are the first species images obtained in spray flames. The laser source for the OH imaging was a Nd:YAG-pumped dye laser providing 10 nsec bursts of tunable radiation near 285 nm, used to excite individual rovibronic transitions in the (1,0) band of OH ($^2\Sigma \leftarrow {}^2\Pi$). Pulsed illumination, freezing the flow for the PMS imaging of the spray, was provided by the same Nd:YAG-pumped dye laser operating near 590 nm.

The significance of this initial work is to confirm the feasibility of PLIF and PMS recording in spray flames. With regard to PMS imaging

APPROACH

DIGITAL IMAGING IN SPRAY FLAMES

PULSED SHEET ILLUMINATION CAN YIELD INSTANTANEOUS IMAGES OF GAS COMPOSITION AND DROPLET SIZE FIELDS



- FIRST 2-D SPECIES IMAGE IN A SPRAY FLAME
- POTENTIAL FOR SIMULTANEOUS IMAGING OF GAS COMPOSITION AND DROPLET SIZE FIELDS

Fig. 4 Approach and sample results for planar Mie scattering (PMS) and planar laser-induced fluorescence (PLIF) in a burning spray.

Hanson & Allen/Stanford Univ.

for characterizing the spray, it should be noted that the droplet spacing (and hence density) is derived immediately from the locations of illuminated pixels. The next step is to demonstrate that the intensity of scattered light, imaged onto a single pixel, can be used to infer the size of the droplet imaged, and work to investigate this possibility is now in progress. Our goal is to establish the capability for simultaneous PMS droplet characterization and PLIF measurements of key species and temperature in burning sprays. Such new capability should enable important advances in spray combustion research.

(d) System Improvements

A major activity during the past year has been to begin assembly of two second-generation solid-state camera systems and a facility for processing image data. In our early work on digital imaging we were forced to design and assemble a one-of-a-kind intensified camera and display system, using components drawn from a number of commercial sources and solving a number of interfacing and software problems on our own. This system was suitable for demonstrating feasibility of PLIF imaging in a variety of reacting flows, but it also had several deficiencies and was not well suited for adoption by user-oriented researchers interested in acquiring similar capability. With the award of a DOD equipment grant for 1984/85, we were able to begin to upgrade our system and to capitalize on the improved performance, availability and compatibility of commercial sub-systems.

A schematic diagram of our planned image acquisition and processing facility is shown in Fig. 5. Items not yet delivered or specified are indicated with asterisks. The facility is housed in the High Temperature Gasdynamics Laboratory (HTGL) at Stanford with the VAX-750 located in the HTGL computer center and the three camera systems, located in separate laboratory rooms, will be linked via an Ethernet. The VAX-750 will also eventually be linked via Stanford's own network (S.U. Net) to other computers and image processing facilities on campus.

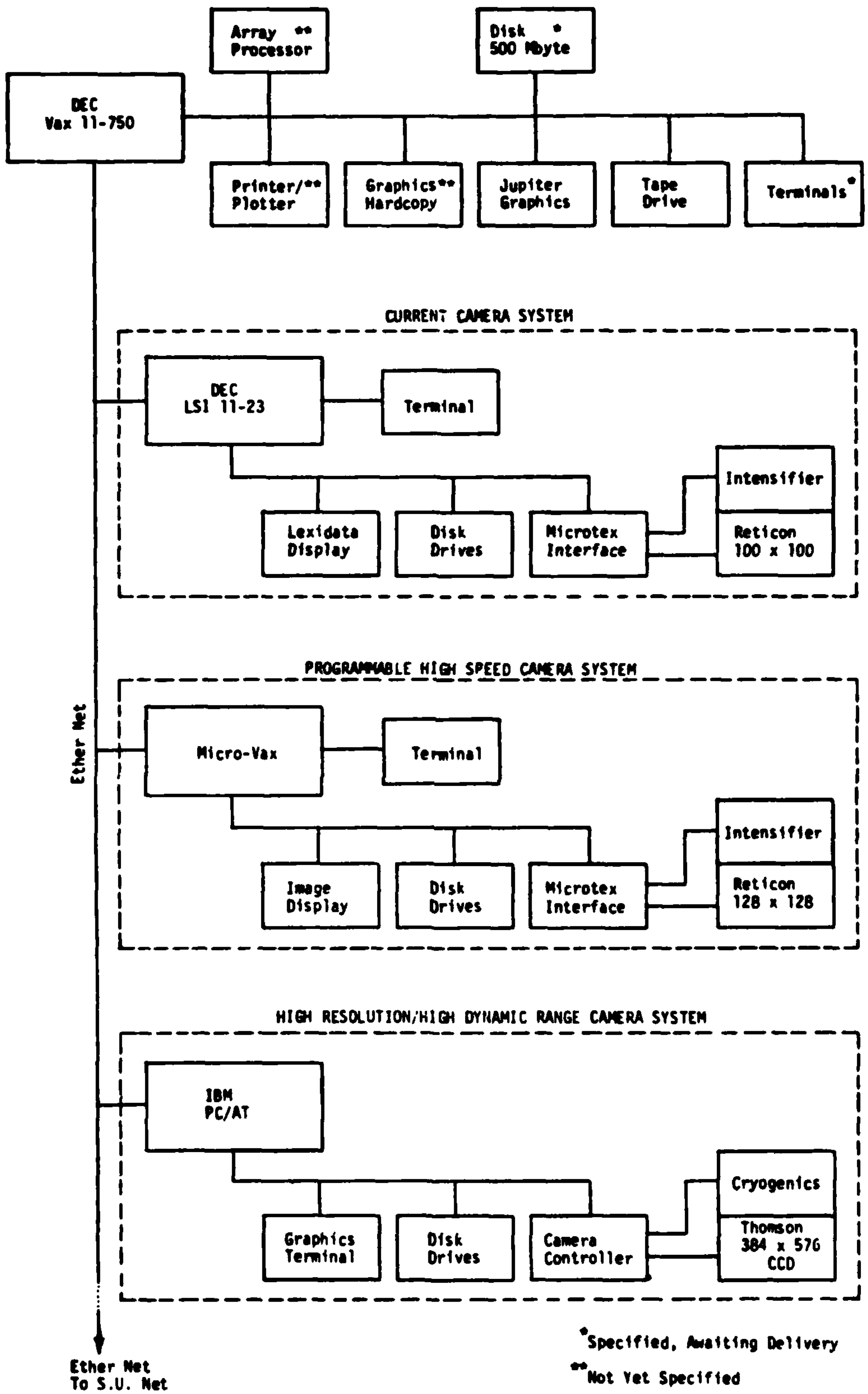


Fig. 5. Schematic diagram of image acquisition and processing facility.

For purposes of this discussion, we consider the facility to consist of three components: detector arrays; dedicated microcomputers for camera control, data acquisition and preprocessing of data; and the central image processing computer. Key characteristics of these components and arguments for the specific items selected are given below.

The selection of the VAX-750 as the image processing computer was prompted primarily by arguments of cost, compatibility with other computers on campus, and availability of peripherals and software for image processing, display and output. We were able to acquire a complete new VAX-750 system for only $60,000, and to this we plan to add an array processor for fast, efficient processing of image data. The large number of VAX systems on campus including several used for image processing applications will result in shared expertise and software and a guaranteed connection to the S.U. Network. Other research groups active in combustion research and flow imaging, including nearby Sandia Laboratories (Livermore) also employ VAX systems, and we expect to benefit from exchanges of information and software from these groups as well.

Our goals for the solid-state cameras were to improve performance and ease of operation. Key performance parameters are noise level, spatial resolution and repetition (framing) rate. We opted for two separate systems, one with low noise and high spatial resolution, and one with programmable framing rate capability. (We call the former the High Resolution/High Dynamic Range System and the latter the Programmable High Speed System.) The virtues of the low noise system are evident in Fig. 6 which plots signal-to-noise ratio versus input photons per pixel (i.e., the "signal") for five separate arrays: intensified and unintensified Reticon arrays, [(100 x 100) or (128 x 128)]; two cooled CCD arrays (Thomson, 384 x 576), one with a standard amplifier and one with a special low-noise amplifier; and a commercially available, high-framing-rate solid-state camera sold by Spin-Physics. The dashed line is the theoretical performance limit set by shot noise statistics. The right-hand boundary of the curves (at 2.5×10^5 photons/pixel for the Reticon array and 1.0×10^6 for the Thomson CCD array) are saturation levels beyond which the system becomes nonlinear.

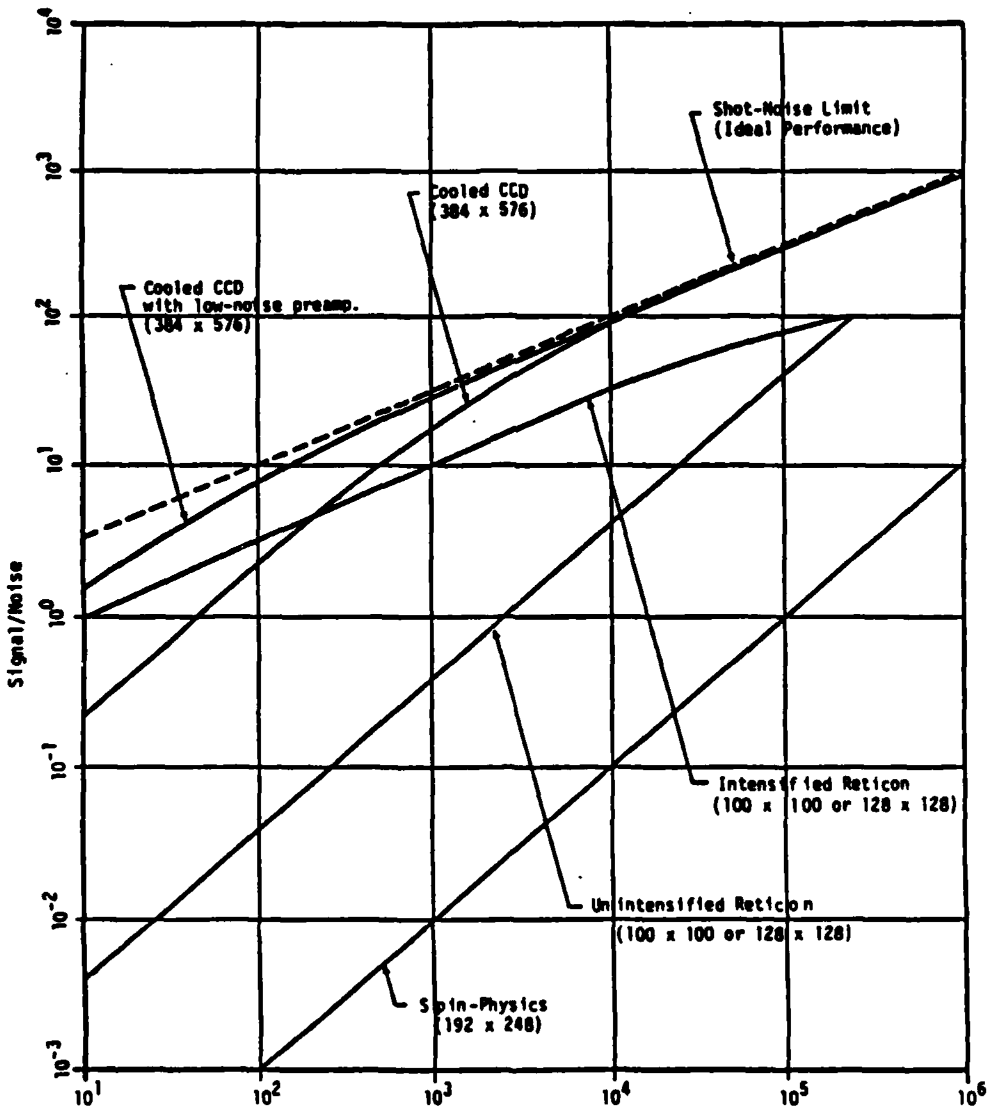


Fig. 6. Signal/noise ratio versus illumination (in photons/pixel) for four array cameras.

We see that the High Resolution/High Dynamic Range System (based on the Thomson CCD with a "standard" amplifier) offers superior S/N over the Programmable High Speed System (based on an intensified Reticon 128 x 128) for light levels above 200 photons per pixel. The curves plotted are a reminder that if we seek a high S/N to enable detection of small changes in flowfield properties, it will be necessary to perform experiments with light levels near their saturation values. At saturation, the cooled CCD will yield a maximum S/N of 1000 while the intensified Reticon and Spin-Physics cameras are limited to about 100, with the

Spin-Physics camera requiring a substantially higher illumination level to reach its maximum S/N. We regard the improved performance of the Hi Res/Hi Dynamic Range System as critical for many experiments, for example in turbulence studies where it may be essential to detect small changes in signal level. As can be seen in Fig. 6, the CCD system equipped with a custom low-noise amplifier actually outperforms the intensified Reticon at all light levels, and it is unintensified, which offers significant cost and operational advantages. The Spin-Physics system is seen to have consistently inferior performance over the illumination level range of interest. The CCD array cryogenics system and camera controller were purchased as a packaged system from Photometrics and are now undergoing set-up and testing in our laboratory.

In addition to the S/N advantages of the CCD system, the array architecture and camera controller appear to offer important advantages for analog processing (averaging) of pixel groups, and "scrolling" and "tracking" of data between exposed and unexposed pixels for fast, burst-mode recording of multiple exposures on a single frame. In this mode of operation, the array acts much like a role of electronic film capable of storing several images. (Actually, the architecture is a double array, 384 x 576 + 384 x 576, which provides capacity for "buffer" storage of data.) In contrasting a CCD-based system to an intensified Reticon system the primary disadvantages are: the need to interface the CCD camera to its dedicated microcomputer, since this has not been done previously; the lack of ultraviolet sensitivity with CCD detectors; and the low framing rate (~10 sec/frame) required to achieve ultra-low-noise performance with the CCD system.

At the present time we are working on the problem of interfacing the CCD camera to the IBM PC/AT microcomputer, and we are carrying out tests to characterize the performance of the camera system. We believe this work is of interest to several groups, and so our results are being written up for distribution as a technical report. To provide the CCD system with ultraviolet viewing capability, we are investigating coating the detector with a material that absorbs ultraviolet radiation and reemits fluorescence radiation in the visible; such materials are known

as "waveshifters". As an alternative, we are investigating recently developed virtual-phase arrays which appear to be sensitive to wavelengths as low as 160 nm.

Our decision to proceed in parallel with a programmable high-speed intensified Reticon camera (128 x 128) was based in part on our previous experience with such an array and the improved availability of packaged system components from Microtex, a vendor which has produced buffer memory and camera controller system components for us in the past. Microtex now markets a complete system (including everything in the dashed box in Fig. 5 labeled Programmable High Speed System), which relies heavily on our experience at Stanford. The system components acquired from Microtex are similar to those now on order by (or delivered to) other groups at Volvo, UTRC, GM Research Labs and Yale University, and will enable programmable trade-offs between framing rate and the number of pixels up to a rate of 2 kHz.

With regard to the dedicated microcomputers for each camera, we've opted for the new DEC Micro-Vax with the Programmable High Speed System, since Microtex will be basing its newest system on that computer, and we've selected the IBM PC/AT because of its high performance/cost figure, the expected wide availability of peripherals and software for the machine, and the potential for cooperation with Photometrics to develop a packaged, advanced performance camera system interfaced with the PC/AT.

Finally, we should note one other system improvement made during the past year, namely the installation and testing of our new 250 Hz excimer-pumped dye laser system which will serve as a high-repetition-rate source for imaging. We found that the laser system delivered met our specifications for power and repetition rate, but the beam quality was not suitable for laser sheet illumination work. Accordingly, we recently installed unstable resonator optics on the excimer, and this change seems to produce the desired uniform sheet beam at 308 nm. In order to generate satisfactory sheet beams at 193 nm (ArF), needed for our work on O_2 imaging, we employ specially coated mirrors and lenses external to the laser.

Publications and Presentations

Presentations

1. G. Kychakoff, K. Knapp, R.D. Howe and R.K. Hanson, "Quantitative Flow Visualization in Combustion Gases", paper No. 82-60, presented at Fall 1982 meeting, Western States Section/The Combustion Institute, Livermore, CA. (October 1982).

2. G. Kychakoff, R.D. Howe, R. K. Hanson and K. Knapp, "Flow Visualization in Combustion Gases," paper 83-0405, presented at AIAA 21st Aerospace Sciences Meeting, Reno (January 1983).

3. G. Kychakoff, R.D. Howe and R.K. Hanson, "Use of Planar Laser-Induced Fluorescence for the Study of Combustion Flowfields," paper 83-1361, presented at 19th Joint Propulsion Conference, Seattle (June 1983).

4. G. Kychakoff, R.D. Howe and R.K. Hanson, "Use of Planar Laser-Induced Fluorescence for Combustion Measurements," presented at CLEO '83, Baltimore (May 1983)

5. G. Kychakoff, R.D. Howe and R.K. Hanson, "Quantitative Flow Visualization Technique for Measurements in Combustion Gases," presented at the Ninth International Colloquium on the Dynamics of Explosions and Reactive Flows, Poitier, France (July 1983).

6. J.C. McDaniel and R.K. Hanson, "Quantitative Visualization of Flowfields Using Planar Laser-Induced Fluorescence," presented at International Flow Visualization Symposium, Michigan (September 1983).

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2.2 Velocity and Pressure Imaging

Introduction

Velocity measurements provide essential input for many fundamental and applied fluid mechanics studies. At present, hot wire anemometry and laser Doppler anemometry are the most commonly used techniques. Both methods have advantages and disadvantages, but in particular they are single-point diagnostics. Clearly, a technique yielding simultaneous multiple-point velocity data would represent a significant diagnostics contribution and could stimulate important advances in many areas involving fluid flow.

Our effort in this area was prompted in part by our success in imaging species at multiple points in a flow (see Section 2.1) and the growing recognition that combinations of flowfield quantities (e.g., species, temperature and velocity) may eventually be needed to test advanced flow models. Accordingly, in 1982 we initiated a new effort to "image velocity", i.e. to measure velocity at a large number of spatially resolved flowfield points leading to a computer display of velocity. Recently, within the past six months, we have conceived three important improvements in our velocity imaging scheme: one idea promises to enable simultaneous imaging of pressure, with great significance for supersonic flow studies; the second idea will allow improved velocity resolution; and the third idea concerns the possible use of O_2 as the molecular velocity indicator, thereby eliminating the need to use corrosive or toxic tracer species. We continue to believe that this general area of research holds still-untapped promise for diagnostics advances.

Scientific Merit

The importance of velocity as a fluid flow parameter is obvious, and so innovation of an improved velocity diagnostic offers broad potential for improved scientific understanding of fluid flows. A successful diagnostic for combined pressure and velocity imaging would represent a sufficiently large advance in measurement capability as to enable first-

time observations of various flow phenomena and possible discovery of unexpected features. The Stanford effort is currently the forefront activity on fluorescence-based velocity imaging in the world. To our knowledge there have been no previous imaging measurements of pressure.

The concept receiving our primary attention, which is based on the velocity modulation (Doppler shift) of molecular absorption lines, offers prospects for a significant improvement over conventional laser Doppler (particle seeding) anemometry for supersonic flows, flows near surfaces (boundary layers) and flows with high acceleration or deceleration where particle lag is a serious problem. Furthermore, multiple-point recording of velocity, and subsequent evaluation of velocity gradients, offers prospects of yielding images of vorticity, a fundamental flowfield variable of growing importance in current fluid mechanics modeling. Extension of our velocity imaging concept to O_2 would be a significant scientific achievement, owing both to the scientific challenges which must be overcome and to the large increase in the utility of velocity imaging which would result.

Status Report

During this last year, work has proceeded on two separate approaches. The first method, for which work has now been completed, involves "marking" specific elements of the flow using laser-excited phosphorescence of biacetyl vapor. Subsequent motion of the marked elements is observed on our intensified photodiode array. A variation of this scheme involving laser-induced formation of sulfur particulates (which can be tracked by Mie scattering) has also been investigated. Both of these projects are now completed and have been described fully in publications (see publications 3, 4 and 8 in list below) and so will not be discussed further here.

Our second scheme, and the one which we believe has the greatest promise, is based on the Doppler effect and involves monitoring the broadband fluorescence from a sheet-illuminated flow using a solid-state array detector. The flow is seeded with a tracer species and a narrow-linewidth cw laser source is used to excite a specific wavelength within

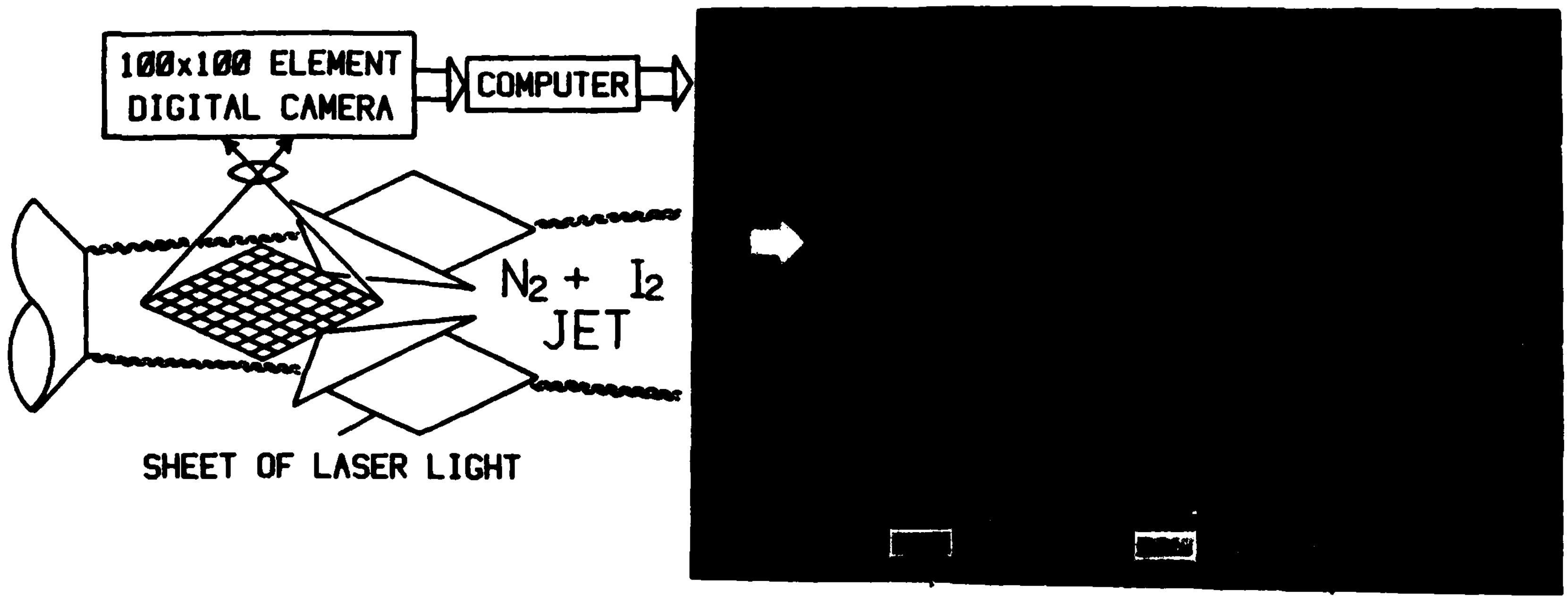
a single absorption line of the tracer species. The fluorescence from a given flowfield point mirrors the absorption occurring there, which for a uniformly seeded flow may depend primarily on the position of the laser wavelength within the absorption lineshape. Since the apparent laser frequency shifts with fluid velocity due to the Doppler effect, the amount of absorption (and hence fluorescence) is a measure of velocity. Iodine (I_2) vapor has been used in the work thus far (because it conveniently absorbs the light at visible wavelengths of tunable Ar^+ and cw dye lasers), although the method is quite general and we have hopes of extending our work to O_2 (see below). Velocity measurements in I_2-seeded, low temperature flows have now been demonstrated for both supersonic and subsonic cases, using somewhat different procedures. Details of the apparatus, procedures and results are available in publications 1,2,5,6 and 7 cited below.

A sketch of the arrangement and typical results for velocity in the centerplane of a subsonic nitrogen round jet are shown in Fig. 1. (Note that the numbering of figures is separate for each major section of this report.) I_2 is seeded into the flow at a trace level of about 300 ppm. A sheet of cw single mode Ar^+-laser light, tuned to a frequency in the wing of the overlapping P(13)/R(15) lines of I_2 ((43,0) band at 514.5 nm), is incident at an angle of 45° to the jet centerline. An intensified photodiode array (100 x 100) camera, imaging the plane of illumination, records the broadband fluorescence emanating from each of the 10^4 imaged locations. The fluorescence signal from each point is proportional to the amount of light absorbed at that point, which in turn depends on the extent of the local velocity-induced Doppler shift of the absorption line relative to the fixed laser frequency (see Fig. 2).

In our initial work, we utilized a single laser frequency and two angles of illumination (to determine two independent velocity components), but recently we have implemented an important improvement based on a two-frequency strategy (see Fig. 2). In brief, we utilize an acousto-optic device to convert the single-mode laser output to two discrete laser frequencies separated by 100 MHz. With this scheme,

2-D Velocity Measurement

- SPATIAL VELOCITY DISTRIBUTIONS VISUALIZED WITH LASER-INDUCED FLUORESCENCE

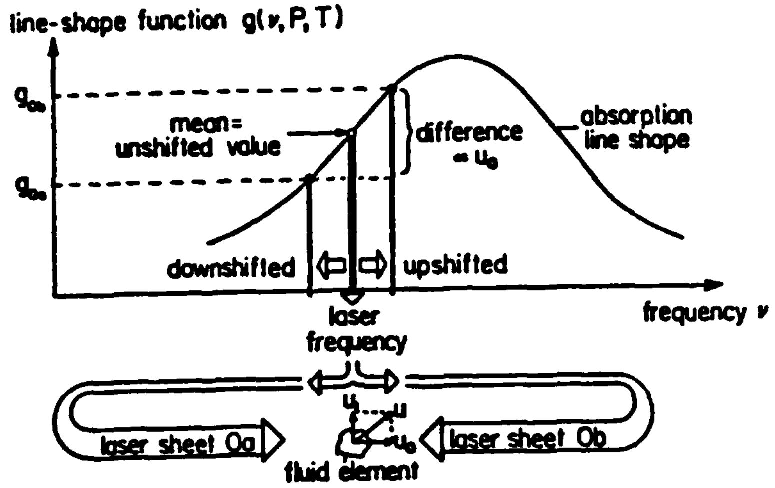


- NOVEL TWO-FREQUENCY TECHNIQUE IS SELF-CALIBRATING
- NO PARTICLE SEEDING REQUIRED
- *FAST DATA PROCESSING; PROSPECTIVE TECHNIQUE FOR REAL-TIME MONITOR*
- SENSITIVITY DEMONSTRATED TO 5 m/s; ACCURACY IMPROVES WITH INCREASING VELOCITY
- POTENTIAL FOR COMBINED VELOCITY AND PRESSURE MEASUREMENTS

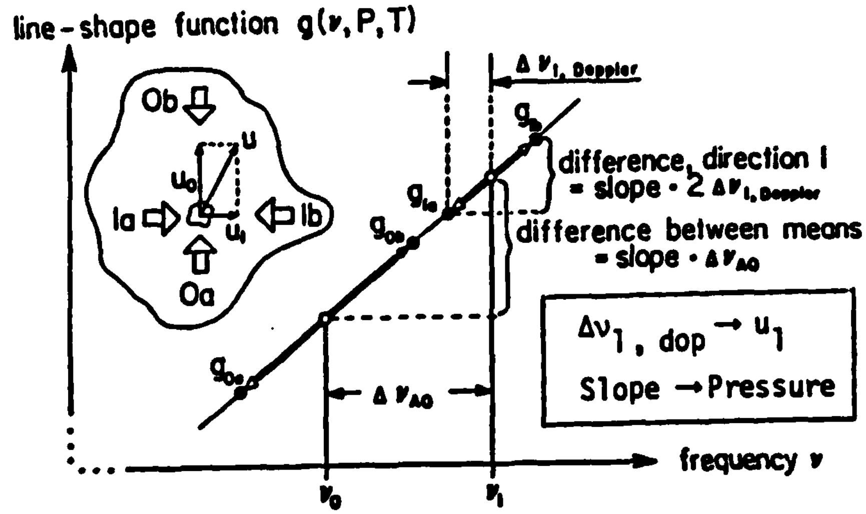
Fig. 1 Approach and results for velocity visualization technique.

Hanson & Hiller/Stanford Univ.

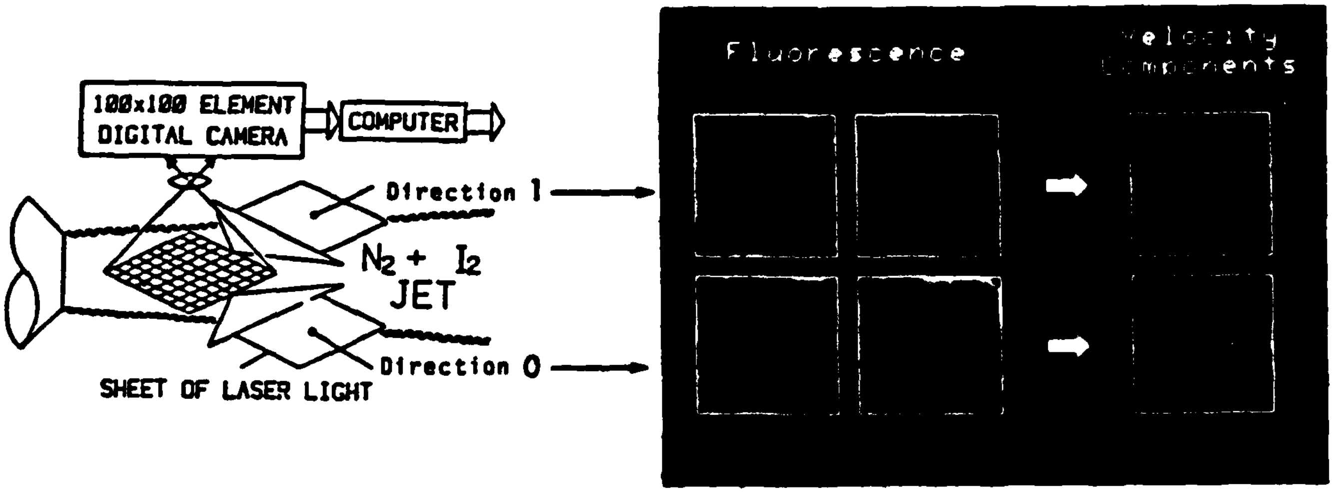
TWO-FREQUENCY STRATEGY FOR VELOCITY AND PRESSURE IMAGING



Effect of Doppler-Shift on Absorption
Line-Shape Function: Single Frequency



Two Laser Frequencies: Provides Self-Calibrated
Velocity and Pressure Measurements



Velocity Data
for
Subsonic Roundjet

Fig. 2 Two-Frequency Strategy for Velocity and Pressure Visualization and Typical Velocity Data for Roundjet.

Hanson & Hiller/Stanford U.

simple differences in the signals from forward and counterpropagating sheets (at a single angle), normalized by the difference in the mean (unshifted) signals at the two frequencies, lead directly to the velocity component for that angle. This scheme is self-calibrating and eliminates the previous requirement to know (by external calibrations) the absorption lineshape function. Of at least equal importance, this new scheme also yields a value for the slope of the absorption line, and this can be a strong function of pressure, thereby opening up the possibility of simultaneous imaging of velocity and pressure. This development could be especially important for supersonic flow studies. Details of this improved approach are given in a recent paper (number 5 on the list below). Figure 3 shows a calculated plot of the normalized slope of the lineshape function which illustrates the expected sensitivity of this measurable quantity to pressure.

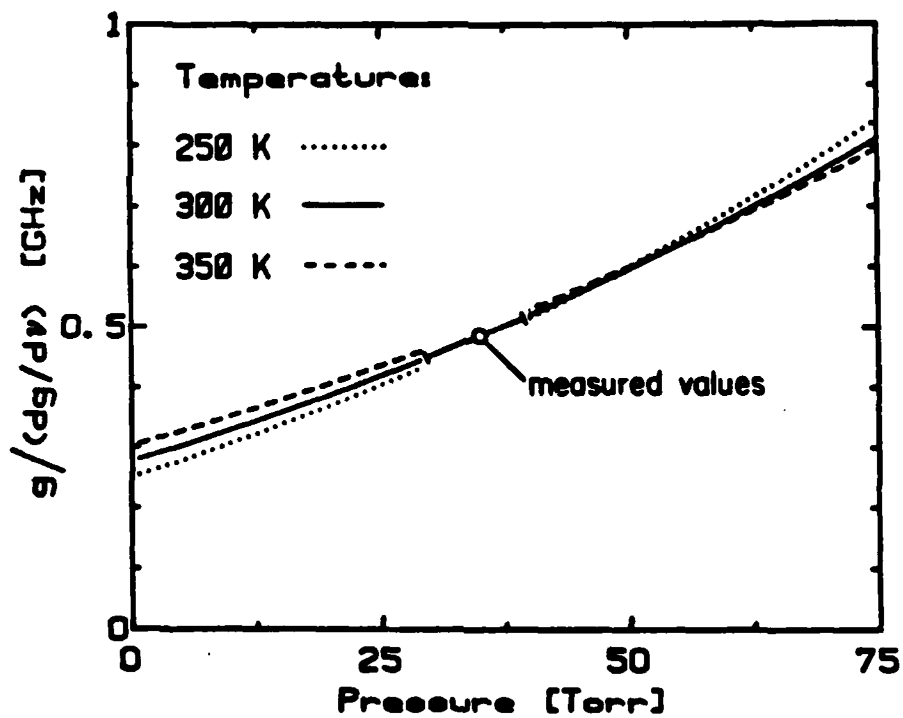


Fig. 3. The function g/(dg/dν) computed from broadening parameters is only weakly temperature dependent and can be used as a calibration curve for pressure measurements. These curves were calculated for a laser frequency fixed at the point of maximum slope for a background pressure of 35 Torr. The 35-Torr point is reproduced by the fluorescence values measured in the flow.

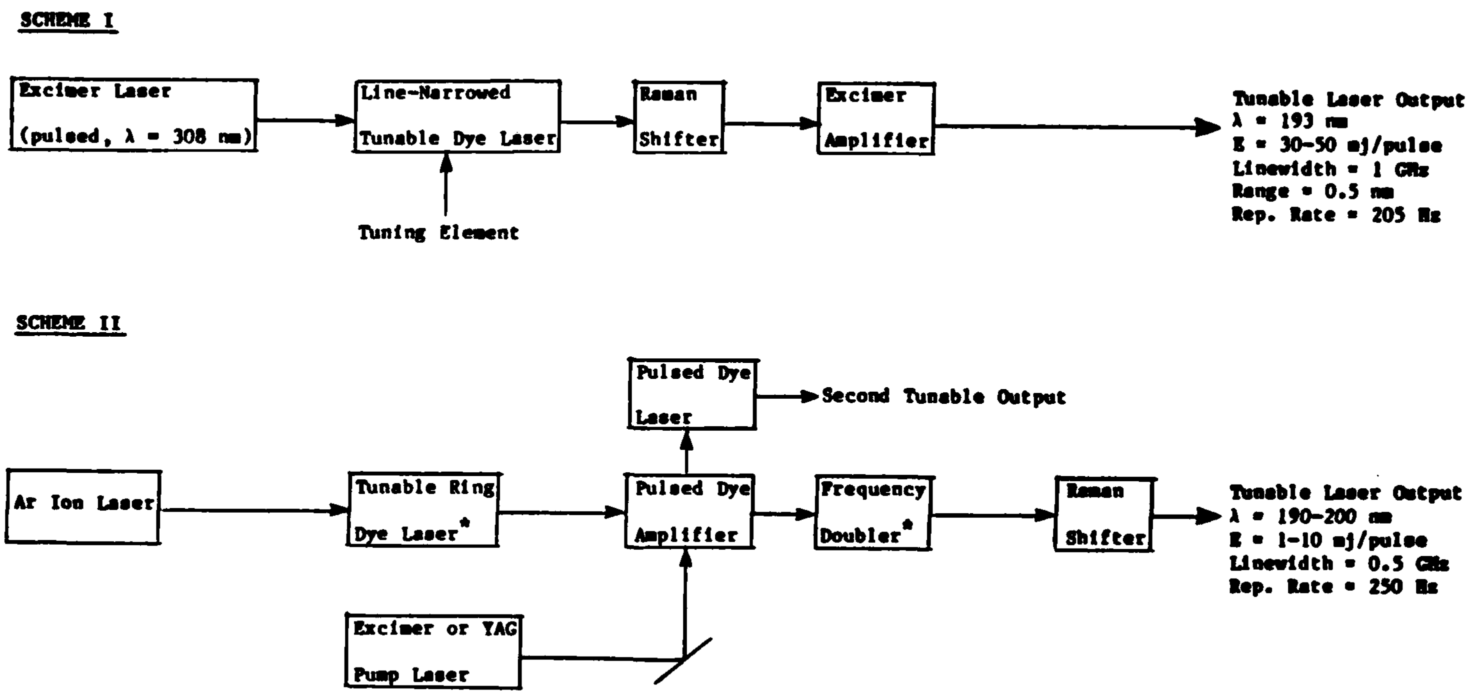
It should be noted that the present scheme uses four camera frames, one for each of four sheets of light, i.e. forward and counterpropagating sheets at each of two angles ($\pm 45^{\circ}$ relative to the jet axis) in the centerplane, to allow determination of the velocity vector in the centerplane of the flow. Although the time required to complete the four measurements is currently about 0.4 seconds, much shorter measurement times are feasible. The sensitivity of the method, currently a few m/s, indicates the capability of the 4-beam technique to probe a variety of low and high Mach number flowfields. The simplicity of the scheme should lend itself to fast on-line data processing. The excellent spatial resolution which can be achieved is an intrinsic feature of laser-induced fluorescence techniques. Current work is being directed toward simplifying the experimental set-up, improving temporal resolution, and testing our strategy for simultaneously inferring pressure from the two-frequency velocity data.

Very recently, as part of planning a research program on supersonic combustion, we've begun to investigate the possibility of performing our imaging velocimetry with molecular oxygen. If an O_2 velocimetry scheme could be developed, of course, this would considerably expand the opportunities to employ velocity imaging in aerodynamics and combustion research, owing to the high levels of O_2 naturally present in many flows of interest. Elimination of seeding trace levels of toxic or corrosive species, such as iodine, would simplify experiments considerably. But oxygen has two other, less obvious but perhaps even more critical advantages, which result from the fact that the O_2 absorption linewidths are large (owing to the effect of predissociation in the excited B state of the Shumann-Runge system) and constant. The first advantage is that large linewidths allow measurements of large Doppler shifts and hence large velocities needed for supersonic flows. The second advantage, which accrues from the constancy of the linewidth and hence lineshape, is that the velocity determination is independent of the gas composition and thermodynamic state. Once we realized these attractive features of using O_2, we turned our attention to solving what we regard as the critical problem, namely the generation of suitably line-narrowed

tunable radiation in the UV to excite O_2 fluorescence. Our research has yielded an encouraging result, which is that these are two candidate laser systems with the proper characteristics which could be assembled from commercially available components. Schematics of the proposed systems are shown below in Fig. 4.

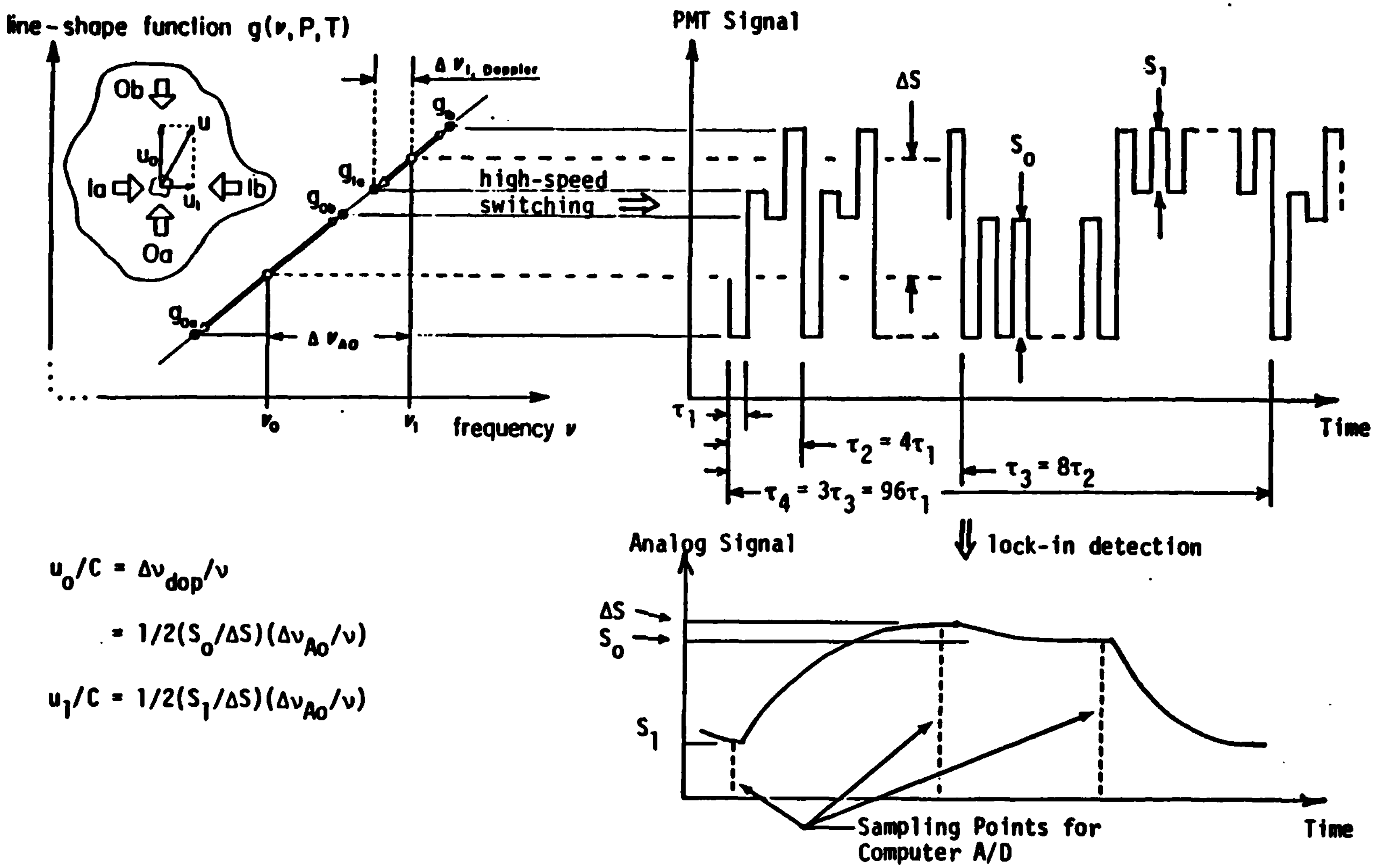
Both of these systems are unique and are, to our knowledge not presently available in any laboratory. Scheme I relies on a 4-step process terminating in an excimer amplifier. We project that this system would have a high energy per pulse (30-50 mj), a linewidth of about 1 GHz, and would operate at repetition rates up to 250 Hz. A potential shortcoming is that the laser would tune over only 0.5 nm, but this should be adequate for O_2 measurements. Scheme II is also a multi-step laser system, comprised of commercially available components. This scheme is more expensive but also has much greater versatility in that it can produce two or more simultaneously tunable output wavelengths. Thus this system would have broadly useful imaging capability for our laboratory, and would provide us with important opportunities for other new research. For the specific purpose of O_2 velocimetry imaging, however, it is expected to have less energy per pulse than Scheme I. We plan to include both of these unique laser systems as key elements in our forthcoming DOD URIP proposal.

We would like to mention briefly another recent idea, based on the same general scheme of Doppler-based velocity imaging, which we believe holds promise and deserves further work. In brief, the idea is to trade off the number of measurement points (pixels) to enable improved temporal and velocity resolution. The proposed scheme, incorporating the same self-calibrating, four-laser-beam strategy, is shown schematically in Fig. 5 for a single detector element. Rather than alternating the four laser sheets rather slowly, as we do currently, we plan to switch the sheets at very high speeds (hopefully 1 MHz) using opto-acoustic modulators and to use analog signal processing of special multi-element high-bandwidth photomultipliers. As an example, we could use a 9-element PMT (giving 9 "pixels"), with each PMT element connected to its own dedicated tuned-filter for analog averaging. A computer would perform



* It may be more efficient to locate the doubling element in the ring dye laser.

Fig. 4 Proposed schemes for production of tunable, narrow-linewidth laser excitation of O_2 for velocity (and pressure) imaging.



$u_0/C = \Delta\nu_{dop}/\nu$

$= 1/2(S_0/\Delta S)(\Delta\nu_{A0}/\nu)$

$u_1/C = 1/2(S_1/\Delta S)(\Delta\nu_{A0}/\nu)$

Fig. 5 Proposed scheme for high-frequency velocity visualization; signals shown for 1 detection element of multi-element PMT detector and 1 channel of multi-channel lock-in system. For $\tau_1 = 10^{-6}$ seconds, velocity measurements at 10 kHz appear feasible.

an A/D conversion at prescribed points on the output waveform of each filter circuit and carry out the needed algebraic manipulations to recover velocity and pressure. Our expectation is that this scheme will lead to substantially improved velocity and temporal resolution in our measurements while still retaining multiple-point capability for determining gradients, more in line with the needs of turbulence research.

Publications and Presentations

Presentations

1. J.C. McDaniel, "Velocity Measurements Using Doppler-Shifted Laser-Induced Iodine Fluorescence," presented at Thirty-Fifth Meeting of the American Physical Society, Div. of Fluid Dynamics, Rutgers U., Nov. (1982).

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6. R.K. Hanson, B. Hiller, E.C. Rea, Jr., J.M. Seitzman, G. Kychakoff and R.D. Howe, "Laser-Based Diagnostics for Flowfield Measurements," invited paper presented at Winter Annual Meeting of ASME, New Orleans, Dec. 9-14, 1984.

7. R. Hanson, "Optical Imaging and Combustion Measurements," invited paper presented at Lasers '84, Symposium on Imaging of Fluids, San Francisco, Nov. 26-30, 1984.

8. B. Hiller and R.K. Hanson, "Combined Measurements of Velocity and Pressure Fields in Compressible Flows Using Laser-Induced Iodine Fluorescence," paper WG4, to be presented at Lasers '85, Las Vegas, Dec. 2-6, 1985.

9. B. Hiller and R.K. Hanson, "Simultaneous Measurements of Velocity and Pressure in Subsonic and Supersonic Flows through Image-Intensified Detection of Laser-Induced Fluorescence," to be presented at AIAA Aerospace Sciences meeting, Reno, Jan. 6-8, 1986.

Publications

1. J.C. McDaniel, B. Hiller and R.K. Hanson, "Simultaneous Multiple-Point Velocity Measurements Using Laser-Induced Fluorescence," Optics Letters 8, 51 (1983).
2. B. Hiller, J.C. McDaniel, E.C. Rea, Jr., and R.K. Hanson, "Laser-Induced Fluorescence Technique for Velocity Measurements in Subsonic Flows," Optics Letters 8, 474 (1983).
3. B. Hiller, R.B. Booman, C. Hassa and R.K. Hanson, "Velocity Visualization in Gas Flows Using Laser-Induced Phosphorescence of Biacetyl," Review of Scientific Instruments 55, 1964 (1984).
4. R.K. Hanson, M.Y. Louge, E.C. Rea, J.M. Seitzman and B. Hiller, "Recent Developments in Absorption and Fluorescence Laser Diagnostics for High Temperature Gases," L.I.A. (Laser Institute of America) Vol. 47 ICALEO (1984), pp. 98-106.
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2.3 Fiber Optic Absorption/Fluorescence Sensors

Introduction

Optical fibers and fiber bundles provide new opportunities for optical diagnostics research and applications. As part of this program, we have in past years made use of optical fibers for transmitting laser light between laboratories and in the construction of intrusive laser absorption/fluorescence probes for species measurements. The recent appearance of relatively inexpensive coherent fiber bundles, suitable for transmitting images, and the apparent (just announced) commercial availability of infrared-transmitting fibers, has encouraged us to initiate new work in this area. Here we summarize our recent work as well as our ideas for new research. In the long term, we are confident that optical fibers will provide the vehicle whereby many sophisticated spectroscopy techniques, proven only under idealized laboratory conditions, can be extended to real-world applications.

We have three new research projects under consideration: (1) an investigation of optical fiber bundles for use with PLIF in internal flow applications; (2) an investigation of infrared fiber sensors utilizing tunable infrared diode laser sources; and (3) an investigation of fiber optic absorption/fluorescence sensors for detecting hot metal atoms or oxides.

The motivation for a PLIF diagnostic useful in internal flows follows directly from the importance of extending modern optical techniques to practical combustion devices, which generally have very limited optical access. And of course, if possible, we would like to have multiple-point measurements as provided by PLIF rather than single-point measurements.

Our interest in exploring infrared-transmitting fibers results from our considerable experience with tunable infrared lasers and the conviction that there are a variety of important measurements which could be made with these lasers, particularly in high pressure and temperature environments, if it were possible to locate them remotely from the experiment of interest.

Our third proposed project is motivated by the potential utility of sensing metal atoms or oxides in hot exhaust streams as an indicator of material degradation in gas turbine combustion systems. Such measurements might be made, for example, using a tunable diode (visible) light source located remotely from the exhaust, in which case the fiber acts only as a conduit of light between the source and the sensor. Both this and the previous project have in common the potential advantage of enabling measurements at multiple locations using only a single source and relatively simple multiplexing ideas.

Scientific Merit

This research seeks to enable the application of spectroscopy-based schemes for remote measurements of gaseous properties in reacting flows. Such schemes are critically needed for flows with poor optical access or where the test environment precludes local placement of a laser source. Our approach is unique in that it seeks to combine recently developed tunable laser sources with novel absorption or fluorescence probes. The resulting diagnostics should be well suited to meet a variety of practical measurement requirements and hence have the potential for significant impact on various scientific and engineering aspects of combustion and propulsion. In addition, our work should contribute substantially to the fundamental spectroscopic data base for high temperature gases.

Status Report

Current effort on this topic involves preliminary planning for the proposed new activities and completion of research projects on remote sensing of NCO and CH in shock tube kinetics and spectroscopy experiments. Other past activities have been published (see list below) and hence will not be discussed here.

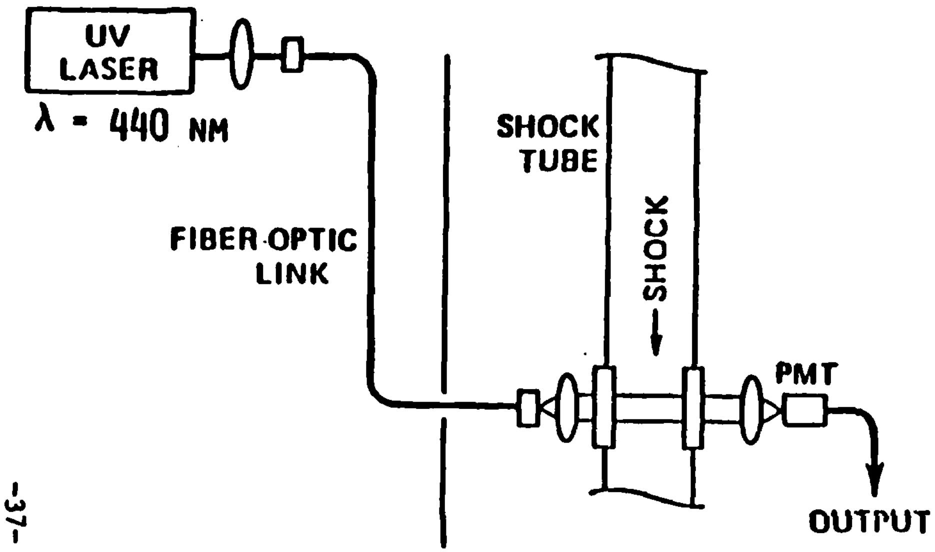
With regard to project planning, we have conducted a complete survey to identify manufacturers of coherent fiber bundles (for imaging) and of infrared-transmitting fibers. In summary, suitable imaging fiber bundles are now available from several manufacturers, but only one company (Galileo) is now willing to deliver (on a test basis) infrared fibers.

Also, we have conducted an unsuccessful survey of manufacturers of visible diode lasers, in the hope of finding a source of wavelength tunable solid-state lasers for use at visible wavelengths appropriate for absorption measurements of metal atoms and metal oxide molecules. It appears that the technology for such lasers is still a few years away; once available, however, these lasers should be relatively cheap and will open up a variety of practical opportunities for sensors in combustion systems.

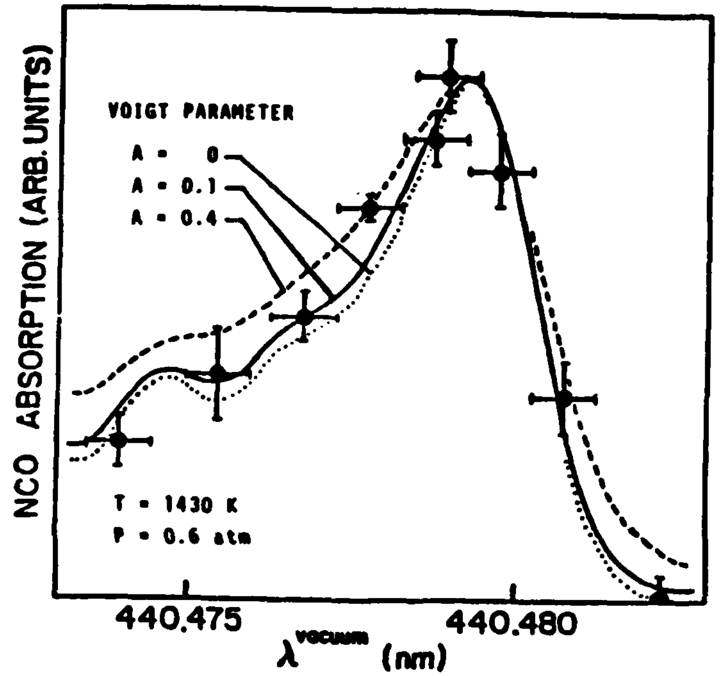
Our major activity during this past year has been to complete measurements of NCO and CH spectral and kinetic parameters using a fiber optic absorption technique to probe these species in a shock tube. Both of these projects have been described in detail in publications (see publications 7-10) in list below) and so only highlights will be presented here. The species NCO has been proposed, on theoretical grounds, as a combustion intermediate of some importance in connection with the chemistry of nitrogen species in combustion. Until now, however, NCO has not been detected in a high temperature system. In our work we have: investigated the electronic absorption spectrum of NCO (B ← X and A ← X bands), found an optimum wavelength for detection, modified our Ar^+-pumped cw ring dye laser to operate at this near-UV wavelength (440 nm, A ← X band), installed a 65 meter optical fiber link between the laser and the shock tube lab, and performed incident shock wave tests to evaluate the spectral absorption parameters of NCO at high temperature. Our measurements of CH were carried out with the same optical arrangements, but with the dye laser set to 431 nm, and represent the first laser-based studies of CH spectroscopy and kinetics in a shock tube.

A schematic of the experiment and typical results are shown in Figs. 1 and 2. The laser source was a ring dye laser (Spectra-Physics 380A) operating on stilbene (S3) dye and pumped by the UV lines (1.9 W, all lines) of an Ar^+ laser (Spectra-Physics 171-18). The output of the laser was amplitude stabilized (Coherent 307 Noise Eater), yielding power levels of 5-10 mW at the input of the 65 meter fiber link (200 micron fused silica fiber, Superguide).

SUCCESSFUL USE OF FIBER-OPTIC LINK TO REMOTELY MEASURE SPECTRAL PARAMETERS OF NCO



Fiber-Optic Link to Shock Tube Experiment

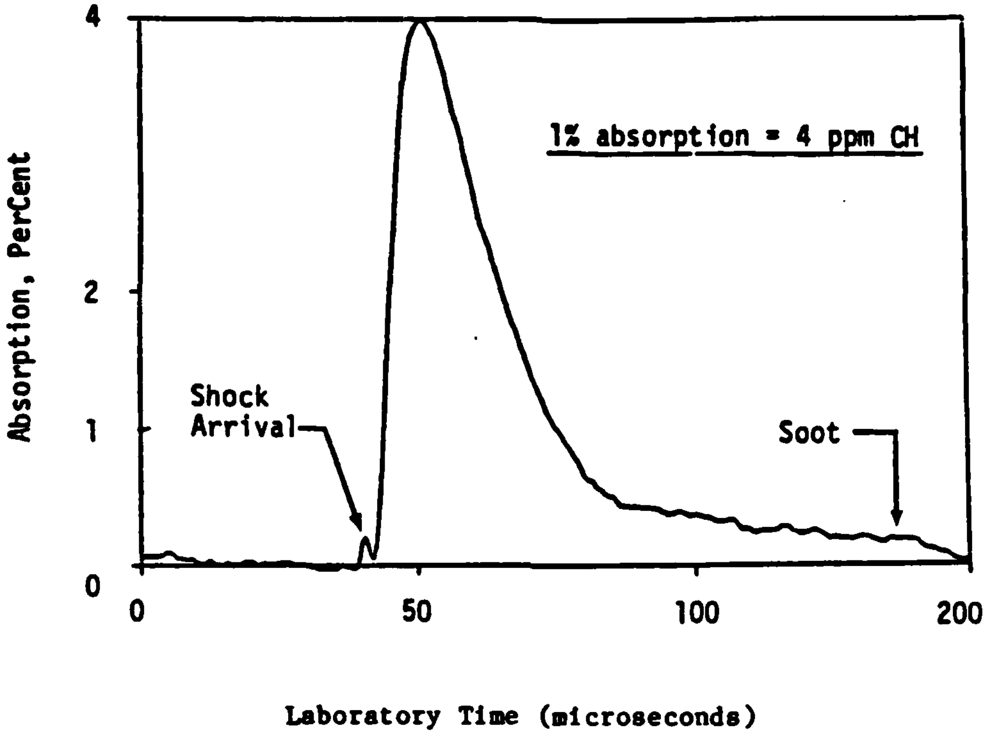


HIGH TEMPERATURE ABSORPTION USED TO INFER NCO OSCILLATOR STRENGTH AND BROADENING FACTOR

- FIBER OPTIC LINK ENABLES USE OF LASER SOURCES FOR REMOTE MEASUREMENTS IN HOSTILE SYSTEMS
- MULTIPLE MEASUREMENT LOCATIONS WITH SINGLE LASER DEMONSTRATED
- FIRST OBSERVATION OF NCO AT HIGH TEMPERATURES
- TECHNIQUE ENABLES DETERMINATION OF SPECTRAL PARAMETERS AT HIGH TEMPERATURES

Fig. 1 Shock tube measurements of NCO spectral absorption coefficient using a remotely located dye laser.

REMOTE LASER ABSORPTION OF CH



λ = 431.1 nm

$Q_{1c}(7) + Q_{2d}(7)$ Lines

T_2 = 2839 K

P_2 = 0.22 atm

Mixture: CH_4/Ar (5/95)

Fig. 2. Remote laser absorption measurements of CH in a shock tube. The ring dye laser, operating single axial mode at 431.1 nm, is located 65 m from the shock tube.

In both the NCO and CH studies the quantity measured was the fractional absorption following shock-wave production of the species. Variations in the absorption as a function of laser wavelength for a fixed level of NCO, as shown in Fig. 1 (for T=1430K, P=0.6 atm), enable determination of the relevant Voigt parameter A and subsequently the collision-broadened linewidth for NCO broadened by Ar. The absolute absorption, together with the known level of NCO present, leads to a value for the electronic oscillator strength. (Details of this work appear in publication 7 below.) A sample data trace for CH absorption in shock

heated CH_4/Ar mixtures is shown in Fig. 2. This record illustrates the sensitivity of the method to detect ppm levels of CH as needed for fundamental studies of hydrocarbon pyrolysis and oxidation kinetics.

The significance of this work is threefold: (1) we have established a new method for quantitatively monitoring NCO and CH, and have made the first laser-based measurements of NCO and CH in a high temperature shock tube system; (2) we have determined oscillator strength and collision-broadening parameters for NCO and CH; and (3) we have demonstrated the utility of fiber optic links for sensitive, quantitative species measurements at locations removed from the laser source. The latter accomplishment suggests the potential of using expensive and sensitive laser sources for measurements at several locations, thereby increasing the utility factor of such systems and enabling sharing of facilities between different experiments and research groups. Furthermore, we have demonstrated the unique capability of combined shock tube - laser experiments for quantitative measurements of fundamental spectroscopic parameters in high temperature gases. This approach should enable important contributions to the scientific data base for combustion gases and plasmas.

Presentations and Publications

Presentations

1. G. Kychakoff and R.K. Hanson, "Optical Fiber Probe Using Tunable Laser Absorption Spectroscopy for Combustion Measurements," presented at 1981 Los Alamos Conference on Optics, April 1981.

2. S.M. Schoenung and R.K. Hanson, "Laser Absorption Sampling Probe for Spatially and Temporally Resolved Combustion Measurements," presented at 1981 Conference on Lasers and Electro-Optics (CLEO), Washington, June 1981.

3. S.M. Schoenung and R.K. Hanson, "Temporally and Spatially Resolved Measurements of Fuel Mole Fraction in Turbulent CO Diffusion Flame," paper WSS/CI 81-33 at Western States Section, Combustion Institute meeting, Phoenix, October 1981.

4. G. Kychakoff and R.K. Hanson, "Tunable Laser Absorption/Fluorescence Fiberoptic Probe for Combustion Measurements," paper WSS/CI

81-50 at Western States Section, Combustion Institute meeting, Phoenix, October 1981.

5. G. Kychakoff, R.D. Howe and R.K. Hanson, "Spatially Resolved Combustion Measurements Using Crossed-Beam Saturated Absorption Spectroscopy," paper THM2 at CLEO '82, Phoenix, Az., April 14-16, 1982.

6. M.A. Kimball-Linne, G. Kychakoff, R.K. Hanson and R.A. Booman, "A Fiber Optic Fluorescence Probe for Species Measurements in Combustors," paper 82-50 at Western States Section, Combustion Institute meeting, Livermore, Ca., October 11-12, 1982.

7. M.Y. Louge and R.K. Hanson, "Shock Tube Study of NCO Kinetics," presented at 20th Symposium (International) on Combustion, Ann Arbor, Aug. 1984.

8. M.Y. Louge and R.K. Hanson, "Shock Tube Study of the High-Temperature Absorption of CH at 431 nm," presented at 15th International Symposium on Shock Tubes and Waves, Berkeley, CA., July 1985.

Publications

1. S.M. Schoenung and R.K. Hanson, "CO and Temperature Measurements in a Flat Flame by Laser Absorption Spectroscopy and Probe Techniques," Combustion Science and Technology 24, 227-237 (1981).

2. S.M. Schoenung and R.K. Hanson, "Laser Absorption Sampling Probe for Spatially and Temporally Resolved Combustion Measurements," Applied Optics 21, 1767-1771 (1982).

3. S.M. Schoenung and R.K. Hanson, "Temporally and Spatially Resolved Measurements of Fuel Mole Fraction in a Turbulent CO Diffusion Flame," 19th Symposium (International) on Combustion, The Combustion Institute, pp. 449-458 (1982).

4. G. Kychakoff and R.K. Hanson, "Optical Fiber Probe Using Tunable Laser Absorption Spectroscopy for Combustion Measurements," The Los Alamos Conference on Optics, 81, D.L. Liebenbert, Ed., Proc. SPIE 288, 236 (1982).

5. R.K. Hanson, S. Salimian, G. Kychakoff and R.A. Booman, "Shock Tube Absorption Measurements of OH Using a Remotely Located Dye Laser," Applied Optics, 21, 641 (1983).

6. G. Kychakoff, M.A. Kimball-Linne and R.K. Hanson, "Fiber-Optic Absorption/Fluorescence Probes for Combustion Measurements," Applied Optics 22, 1426 (1983).

7. M.Y. Louge and R.K. Hanson, "Quantitative High Temperature Absorption Spectroscopy of NCO at 305 and 440 nm," J. Quant. Spectrosc. and Radiat. Transfer 32, 353-362 (1984).

8. M.Y. Louge and R.K. Hanson, "High Temperature Kinetics of NCO," Comb. and Flame 58, 291 (1984).

9. M.Y. Louge and R.K. Hanson, "Shock Tube Study of NCO Kinetics," 20 Symposium (International) on Combustion, The Combustion Institute, pp. 665-672 (1984).

10. M.Y. Louge and R.K. Hanson, "Shock Tube Study of the High-Temperature Absorption of CH at 431 nm," in Shock Waves and Tubes, ed. D. Bershades adn R.K. Hanson, Stanford Univ. Press, in press.

11. M.A. Kimball-Linne, G. Kychakoff and R.K. Hanson, "Fiberoptic Absorption/Fluorescence Combustion Diagnostics," submitted to Comb. Sci. & Technol., June 1985.

Personnel

Ronald K. Hanson	Professor, Mechanical Engineering
Susan Schoenung	Graduate Student, Mechanical Engineering (Ph.D. awarded in June 1982)
Mark A. Kimball-Linne	Graduate Student, Mechanical Engineering (Ph.D. awarded in December 1984)
Michel Y. Louge	Graduate Student, Mechanical Engineering (Ph.D. awarded in December 1984)
George Kychakoff	Asst. Prof. (Acting) Mechanical Engineering (Ph.D. awarded in March 1985)
Anthony Dean	Graduate Student, Mechanical Engineering (Ph.D. expected in June 1989)

2.4 Laser Wavelength Modulation Spectroscopy

Introduction

Recent improvements in tuning rates of narrow-linewidth laser sources offer opportunities for establishing a new class of diagnostic techniques based on wavelength modulation spectroscopy concepts laser wavelength modulation spectroscopy refers to laser absorption or laser-induced fluorescence measurements carried out with a rapid-tuning single mode laser. In essence this method involves quickly scanning a tunable cw laser across one or more isolated absorption transitions and recording the spectrally resolved absorption line profile using either absorption or fluorescence detection. The method is generally applicable to both infrared and UV/visible transitions, and it is particularly attractive for measurements in combustion gases and plasmas.

A primary advantage of wavelength modulation is that it provides a simple means of discriminating against continuum extinction and luminosity effects, which can seriously hinder conventional laser absorption or fluorescence measurements in two-phase combustion flows and high-luminosity plasmas. Moreover, recording the fully resolved absorption line eliminates the need for uncertain linewidth assumptions in converting measured absorption (or fluorescence) to species concentration or temperature. Previously in our laboratory, in AFOSR-sponsored work, we demonstrated the utility of the wavelength modulation concept for combustion measurements involving infrared-active species using a commercially available rapid-tuning infrared diode laser.

Unfortunately, rapid-tuning dye lasers, needed for accessing a variety of important radical species which absorb in the near UV and visible, are not commercially available. Recognizing the importance of such a capability, we developed (under AFOSR support) a novel and simple modification to a commercial ring dye laser which increases the scan repetition rate by three orders of magnitude (from about 4 Hz to 4 kHz) for short scans (up to 5 cm^{-1} = 150 GHz), and we have recently incorporated intracavity frequency doubling into the dye laser to permit access to UV wavelengths. Operation in the UV is critical for access to a variety of important combustion and plasma species.

Scientific Merit

Our laboratory now has unique capability and experience with fast-tuning lasers (UV, visible and IR) and wavelength modulation spectroscopy. This capability provides several opportunities for pioneering contributions to combustion and plasma diagnostics research. In connection with combustors where particulates or droplets are present, wavelength-modulation techniques can be applied to discriminate between the gaseous absorption or fluorescence of interest and interfering continuum extinction. For plasma flows which may be highly luminous, wavelength modulation should provide a means of distinguishing the spectrally varying signal of interest from the intense continuum background. In unsteady flows or in devices where transient phenomena are of interest, fast measurements of fully-resolved absorption or fluorescence lines can be used for time-resolved determinations of species and temperature. Finally, the significance of fast-scanning capability for fundamental spectroscopic measurements should be noted. For example, we have recently demonstrated, for the first time in any laboratory, the feasibility of recording fully resolved absorption lines in shock tube flows. Such experiments provide unique capability for obtaining a variety of fundamental high-temperature data including important quantities such as collision linewidths, oscillator strengths and heats of formation; these parameters are needed to enable quantitative absorption and fluorescence measurements of species in combustion and plasma flows.

Status Report

The dye laser modification which enables fast-tuning laser wavelength modulation spectroscopy has been described previously (see publications 1 and 6 below). We have utilized this new laser system in two novel experiments, one conducted with a shock tube (see publication 6) and one in a flame (see publication 5). Here, for purposes of illustrating the unique capabilities of the laser, we show very recent results obtained in shock tube experiments. In these experiments, the laser was used to record fully resolved absorption line profiles of OH over a range of post-shock conditions. In brief, the center frequency of

the repetitively scanning laser was set on a known UV line of OH, and the beam was passed through the shock tube to enable recording of absorption line profiles behind incident shock waves. Mixtures of $H_2/O_2/Ar$ were shock heated to provide relatively constant levels of OH at known conditions. These experiments provide the first fully resolved, radical species absorption spectra recorded in a shock tube, and they can be used to infer fundamental parameters, such as collision-broadened linewidths, about which very little is known at high temperatures. A schematic diagram of the experiment is shown in Fig. 1, and a sample data trace is shown in Fig. 2.

Figure 3 provides a preliminary plot of the rotational quantum number dependence of the Argon-broadened linewidth of OH at 2000K, extracted from data traces similar to that shown in Fig. 2. These are the first directly determined data for this fundamental quantity. Figure 4 provides a plot of the temperature dependence of the collision linewidth for a specific rotational transition. The practical implication of the work is that it will enable more quantitative species measurements of OH (by absorption or fluorescence) in combustion systems.

The important conclusion to be drawn from our work on laser wavelength modulation spectroscopy is that these new techniques, in conjunction with shock tube methods, clearly enable new opportunities for fundamental and applied research on spectral and thermochemical properties of high temperature gases.

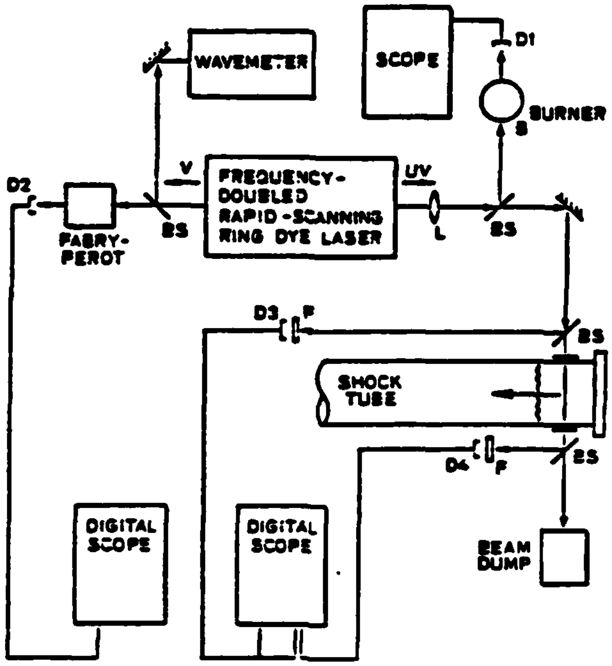


Fig. 1 Schematic diagram for fast-scanning dye laser absorption experiments behind reflected shock waves.

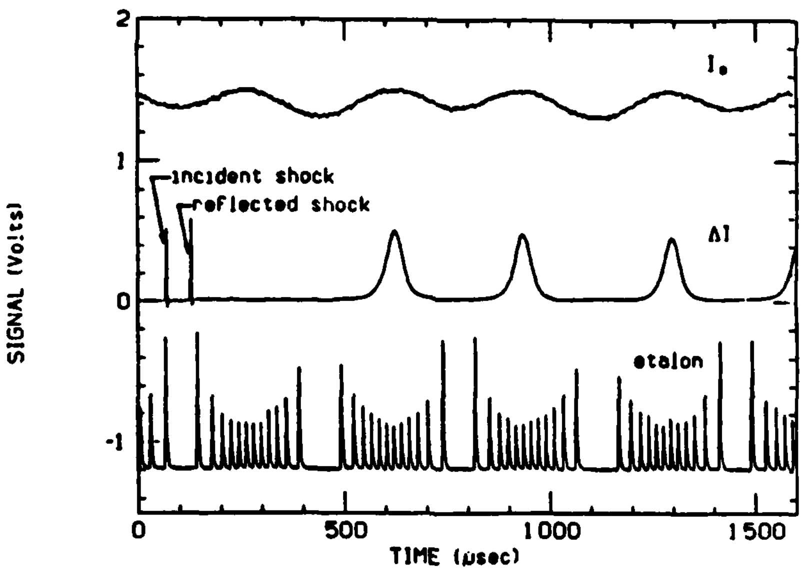


Fig. 2 Sample records of I_o, $\Delta I = I_o - I$, and etalon trace versus lab time for $R_1(5)$ line of OH at 306.7 nm. Postshock conditions: T_5 = 1960K, P_5 = 4.30 atm. Preshock mixture = 500 ppm H_2, 500 ppm O_2, balance Ar. The etalon fringe spacing corresponds to frequency changes of 4 GHz = 0.133 cm^{-1} in the UV.

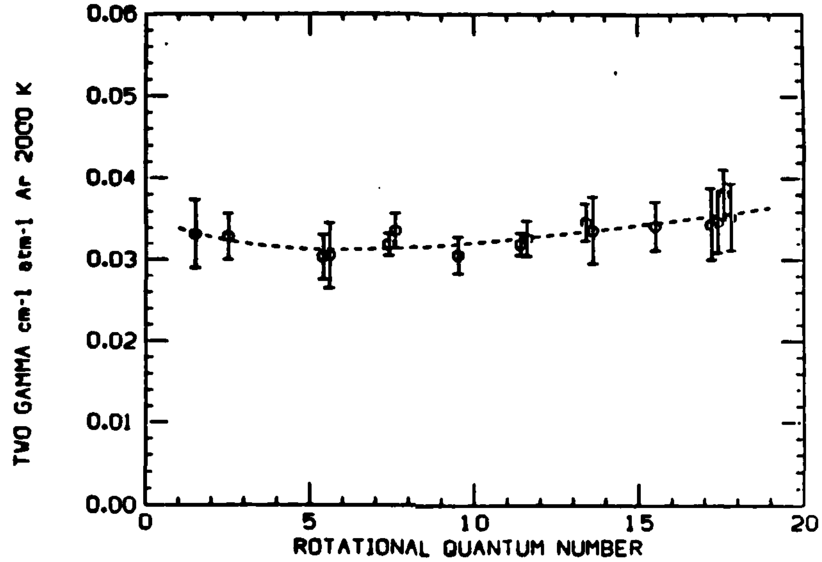


Fig. 3 J-dependence of the collision linewidth for Ar broadening at T_5 = 2000K.

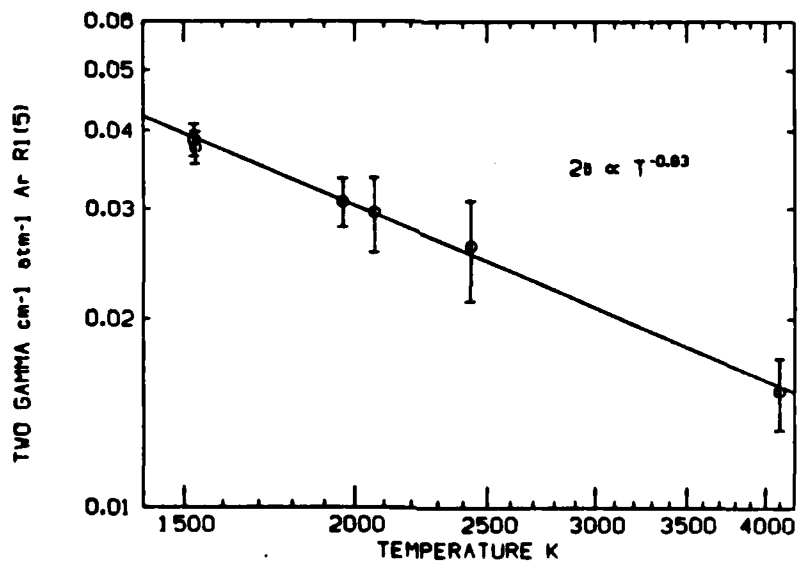


Fig. 4 Temperature dependence of the collision linewidth for Ar broadening; $R_1(5)$ line at OH. Best-fit temperature exponent is n = 0.93.

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1. E.C. Rea, Jr., and R.K. Hanson, "Rapid Extended Range Tuning of Single-Mode Ring Dye Lasers," Applied Optics 22, 518 (1983).

2. E.C. Rea, Jr. and R.K. Hanson, "Fast-Scanning UV Ring Dye Laser for Combustion Research," presented at CLEO '83, Baltimore (May 1983).

3. R.K. Hanson, S. Salimian and E.C. Rea, Jr., "Laser Absorption Techniques for Spectroscopy and Chemical Kinetics Studies in a Shock Tube," in Shock Tubes and Waves, ed. R. Archer and B. Milton, Sydney Symposium Publishers, 595-601 (1983); presented at 14th International Symposium on Shock Tubes and Waves, Sydney, Aug. 19-22 (1983).

4. R.K. Hanson, "Tunable Diode Laser Measurements in Combustion Gases," SPIE Vol. 438, pp. 75-83 (1983); also presented at 1983 meeting of Soc. Photographic and Inst. Engineers, San Diego, August 1983.

5. E.C. Rea, Jr. and R.K. Hanson, "Fully Resolved Absorption/Fluorescence Lineshape Measurements of OH Using a Rapid-Scanning Ring Dye Laser," paper 83-66 at the fall meeting of the Western States Section/Combustion Institute, Los Angeles, CA, October 1983.

6. E.C. Rea, Jr., S. Salimian and R.K. Hanson, "Rapid-Tuning Frequency-Doubled Ring Dye Laser for High Resolution Absorption Spectroscopy in Shock-Heated Gases," Applied Optics, 23, 1691-1694 (1984).

Personnel

Ronald K. Hanson	Professor, Mechanical Engineering
E.C. Rea, Jr.	Graduate Student, Mechanical Engineering (Ph.D. Expected in June 1986)

2.5 Plasma Diagnostics for Energy Conversion Research

Introduction

An emerging element of our overall program is research on plasma diagnostics which will be of subsequent use in fundamental research on plasmas and in studies of various plasma-related energy conversion schemes.

Primary motivation for this work arises from renewed interest in advanced space power and propulsion systems which may involve plasmas. Among the systems under consideration are thermionic converters and MHD generators for electrical power generation, MPD thrusters and beamed laser energy for propulsion, and direct production (in space) of high-power laser radiation for beamed energy. Considerable research will be needed before optimum systems for space utilization are identified, developed and placed in service, and we believe that advanced diagnostics will play an important role in such research. Furthermore, the initiation of work on plasma diagnostics forms a logical, efficient extension of our current program.

Scientific Merit

This research seeks to provide new diagnostic methods for use in studies of plasma properties and plasma phenomena. The two primary techniques which we are pursuing, namely PLIF imaging and wavelength modulation absorption/fluorescence, are novel and will provide unique capabilities for measurements in ionized gases. We intend to coordinate this work closely with other OSR-sponsored work on plasma sciences underway in our laboratory, and we expect the scientific merit and relevance of the work to be enhanced by these interactions.

Status Report

This research is still in an early stage and our work has consisted primarily of literature reviews, paper studies of candidate diagnostic techniques and plasma facility assembly. On the basis of this background work, we have narrowed our selection of diagnostics topics to three

approaches: (1) quantitative visualization (imaging) of plasmas using PLIF, i.e. simultaneous multiple-point laser-induced fluorescence measurements of plasma parameters such as species concentration (including ions and electrons), temperature and electric field strength; (2) wavelength modulation spectroscopy using laser absorption and/or fluorescence; and (3) other laser scattering concepts. To put our work in focus, we are particularly interested in techniques which have promise for measurements with high spatial resolution, for example near electrodes and boundaries where discharge and erosion phenomena are of importance, and in finding new, improved methods for quantities such as temperature, electron number density, ion species concentrations and electric field strength.

A block diagram indicating the laser systems to be employed, the techniques of interest, and the plasma systems to be studied, is given in Fig. 1. Two of the three laser systems indicated, providing tunable cw dye laser radiation (280-700 nm, with some gaps) and tunable pulsed dye laser radiation (220-900 nm), are already on hand. We also plan to provide new capability to access tunable vacuum ultraviolet (VUV) wavelengths by adding a Raman shifter (cell of H_2 at high pressure) to our pulsed dye laser. This addition will allow access to the absorption/fluorescence spectra of a variety of atomic species of importance in plasma and electrode phenomena studies.

We plan to conduct research in two widely separate plasma regimes: low-pressure discharges and high-pressure, inductively heated plasmas. The low pressure facility is now complete except for the microwave power supply. In brief, the viewing chamber is a stainless steel box, with windows on all four sides, and electrodes mounted on removable top and bottom plates. The chamber is coupled to an inlet gas manifold, for varying the input gas composition and flow rate, and to a vacuum pump. We have paid particular attention to optical access so that we will be able to demonstrate the ability to measure with high spatial resolution near surfaces (electrodes) and with high temporal resolution in transient discharges.

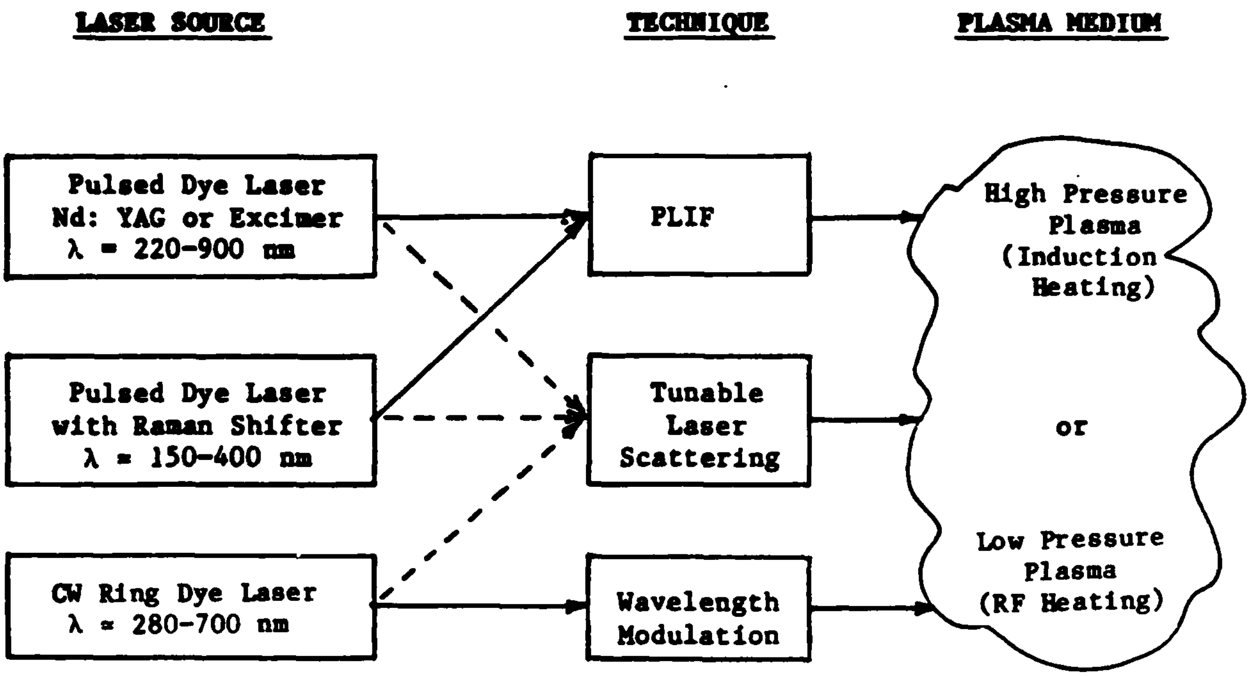


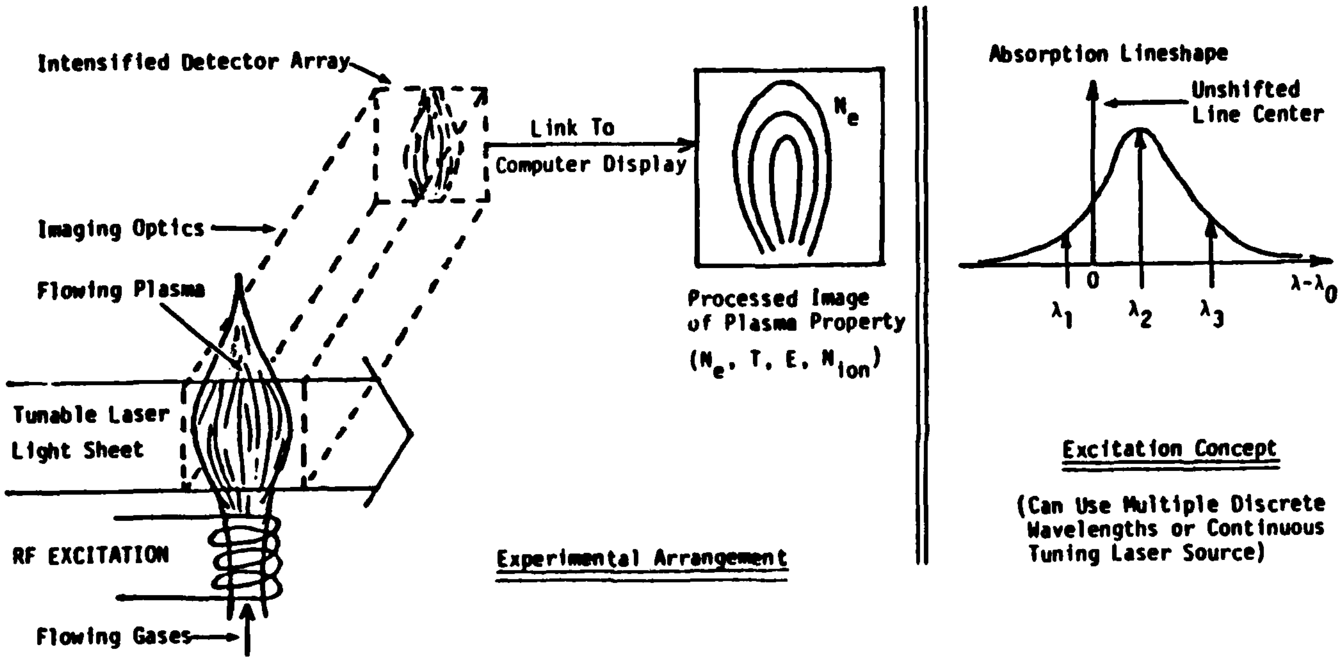
Fig. 1 Laser Systems and Techniques for Plasma Diagnostics Research.

With regard to the high-pressure facility, we have conducted preliminary work with a low power (10 kW) induction-heating power supply acquired on surplus. This system provides nearly ideal optical access for diagnostics studies and, subsequently, research on a variety of plasma sciences topics (e.g., plasma processing, for powders and gases; laser-plasma interactions and energy transfer; and non-equilibrium aspects of plasmas). It now appears, however, that this induction-heated torch has insufficient power to generate interesting plasma conditions, and further work along this line must await purchase of a higher power plasma generator. Funding of such a system will be included as part of our forthcoming DoD URIP proposal.

The status of our work on plasma diagnostics is that we have reviewed a variety of candidate measurement ideas, leading to the three categories of techniques noted above, and one student is now proceeding with category (1), namely planar laser-induced fluorescence (PLIF) plasma measurements. A schematic diagram of the planned approach, and a listing of some key attributes, is given in Fig. 2. Our plan, once a

FLUORESCENCE-BASED IMAGING TECHNIQUES FOR QUANTITATIVE 2-D PLASMA MEASUREMENTS

- Use of array detectors to record planar laser-induced fluorescence offers potential for quantitative imaging of plasma properties



- 2-D Fluorescence Imaging Offers Major Advantages Over Line-of-Sight/Abel Inversion Approaches
- Use of Multiple Excitation Wavelengths Enables Probing of Lineshapes and Shifts which Contain Information on Plasma Properties
- Use of Low-Lying and High-Lying Transitions Offers Potential For Combined Measurements of N_e, T, E and N_{ion}

Hanson/Stanford University

Fig. 2 Key features of PLIF as a plasma diagnostic technique.

suitable plasma torch is available, is to set-up a PLIF system and establish procedures for monitoring the properties of interest: ion concentrations, temperature and electron number density. As an example, our plan for electron density (n_e) is to make use of the known relationship between the Stark-broadened absorption lineshape function and n_e. We intend to excite three (or more) different wavelengths within a specific absorption line (see Fig. 2), and to use the ratio of the resulting LIF signals (at each flowfield point or pixel) to establish the width and shift of the line, and hence n_e as well as possibly T. Some calculations to select optimum wavelength positions within a line, and to select suitable species and transitions, will be needed to guide the experiments. In most respects, the experimental PLIF arrangement will be similar to that employed in our combustion research.

There is of course a requirement to match the wavelengths of the exciting laser system with the absorption spectra of molecules of interest, and so our initial experiments will be influenced by the tunable laser sources currently in our laboratory. More specifically, we plan to utilize both our tunable cw dye laser (which can provide narrow-linewidth output in the ranges λ = 280-310 nm, 340-345 nm and about 500-700 nm) and our tunable pulsed dye laser (broadband output in the range λ = 220-900 nm) as laser sources in PLIF experiments. In addition, we plan to acquire a Raman shifter, to be pumped by either our pulsed dye laser or our excimer laser itself, which will provide access to wavelengths in the VUV. A curve based on preliminary calculations of output pulse energy versus wavelength is shown in Fig. 3. Note that we expect to be able to reach all wavelengths down to about 160 nm with a pulse energy of at least 1 microjoule. Using fixed-frequency excimer lines we can generate higher pulse energies at discrete wavelengths. The values shown correspond to the specifications of our excimer and excimer-pumped dye laser. We are presently carrying out a survey of absorption spectra of relevant compounds which fall in this spectral region. Further literature searches regarding spectra of relevant neutral and ionized atoms and molecules will be carried out as part of this research.

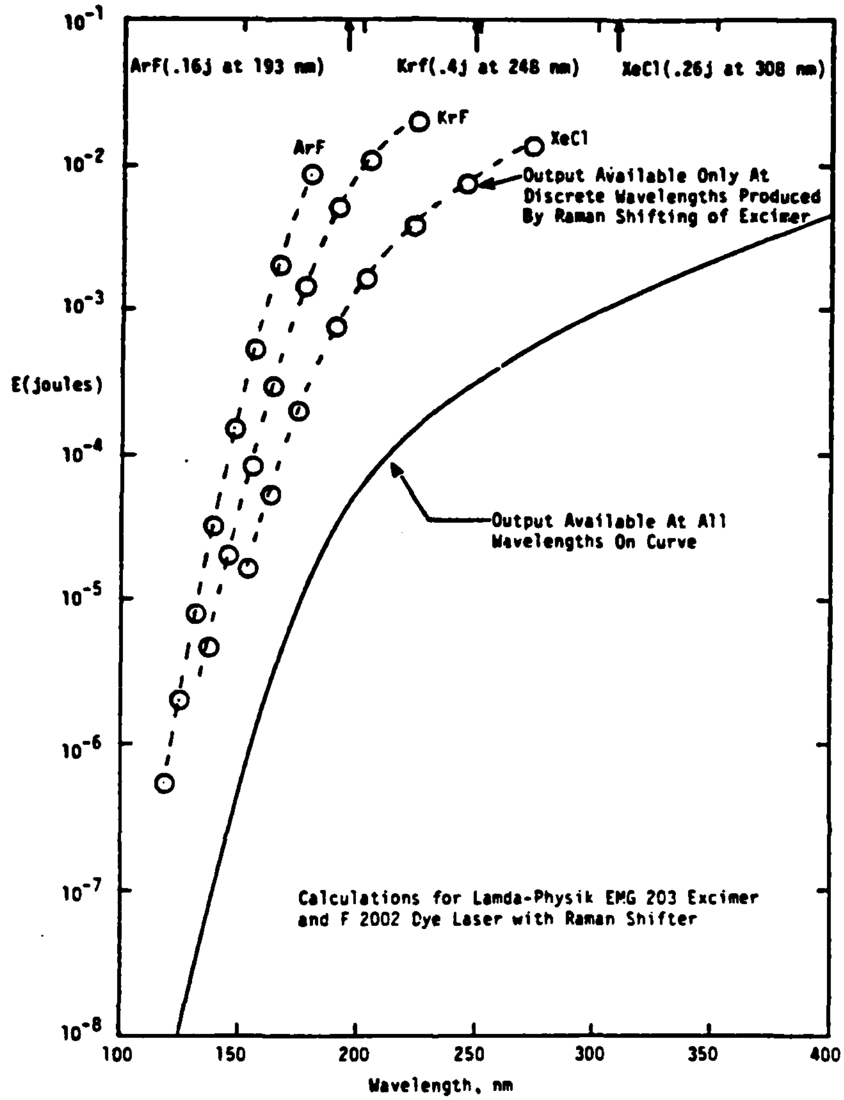


Fig. 3 Output energy per pulse for: discrete wavelengths produced by Raman shifting Lambda-Physik EMG 203 excimer laser; and continuous wavelengths produced by Raman shifting F2002 pulsed dye laser.

The second category of techniques to be explored is wavelength modulation spectroscopy. Our ideas here are less well defined, but in brief we wish to explore the utility, for plasmas, of the same approaches we are currently establishing for combustion measurements. The wavelength regions we can access with our fast-tuning cw UV/visible and IR laser systems are somewhat limited, and so one of our first

activities is to become more familiar with the absorption/fluorescence spectra of the species accessible in our plasma torch or low pressure plasma facilties. Once these plasma facilities are operational, we will conduct an absorption-based spectral survey of the plasma to identify suitable spectral features which can be used in our work to establish measurement strategies. Our hope is that fully resolved fluorescence measurements will yield, through the apparent linewidths or line shifts, information on plasma properties such as electron concentration or temperature, in addition to the local species concentration for the absorbing neutrals and ions.

Finally, and on a more speculative basis, we wish to explore laser-based scattering techniques for plasma measurements. As a first example, we would like to pursue a novel concept for determining the electron number density via measurements of the plasma frequency, the latter being a characteristic local frequency of the plasma which is a known function of the electron number density. Our idea, which is untested, is to cross two lasers at a point, and to vary the laser frequency difference until it matches the plasma frequency. At this point the plasma will be excited and should exhibit, we hope, enhanced scattering of light at one of the incident wavelengths. The scattered light, present only when the separation in laser frequencies matches the plasma frequency, is simply an indicator of when the matching condition is satisfied. The frequency itself will be inferred from simple etalon traces of the laser and hence should be very precise. Although this idea is in a preliminary stage, it illustrates the type of new approach we would like to take in this work. A second idea would be to utilize depolarization effects present in plasmas to perform a cross-polarization form of Rayleigh scattering to infer plasma properties such as the electric field strength.

Publications and Presentations

None

Personnel

Ronald K. Hanson	Professor, Mechanical Engineering
Phillip Paul	Research Associate, Mechanical Engineering
Doug Baer	Graduate Student, Mechanical Engineering (Ph.D. Expected in June 1988)

2.6 LASER INTERACTIONS WITH PLASMAS AND COMBUSTION GASES

Introduction

We wish to begin to combine our diagnostics research with research on laser-material interactions, and accordingly we have given consideration to possible studies of laser interactions with plasmas, solid surfaces, particle (or droplet) clouds, and combustible gases. Each of these areas pose scientifically interesting research problems, relevant to the broad field of energy conversion, and would benefit from the application of diagnostic capabilities available in our Laboratory. We feel that we are in a particularly good position to perform research on laser-plasma interactions and on interactions of tunable lasers with fuel-oxidizer systems for ignition of combustible mixtures or perturbation (energy addition or chemical changes) of already burned gases. The latter area is often described as photo-enhanced combustion.

Status Report

Work thus far has consisted of planning possible projects and doing the necessary literature studies to assess the current status of these areas. On the basis of this work, indicated in the Introduction, we have narrowed our consideration to two topics: interactions of lasers with combustion gas systems, and studies of laser-produced plasmas.

Our plans for laser-combustion gas studies are not thought through in detail but are motivated by the following considerations. We believe that tunable lasers offer new opportunities for stimulating and controlling chemical reactions in combustible systems. Basic research possibilities range from fundamental studies of chemical kinetics (including ignition) to questions of beamed energy transfer to combustion media (for propulsion applications or safety/damage studies). With regard to chemical kinetics, for example, we believe that laser photolysis, using a tunable excimer laser together with shock wave heating, offers exciting prospects for a unique new approach to studying reactions of reactive radical species at high temperature. The basic idea is to shock heat gases and then trigger specific chemical reactions

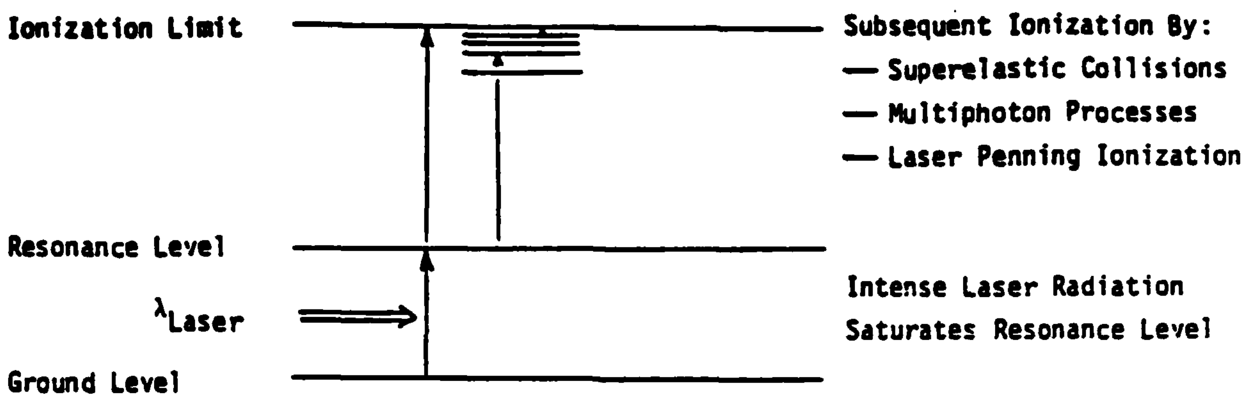
in the high temperature gases using tuned-laser photolysis. In the area of radiative coupling to combustible media, there are interesting fundamental and practical questions as to whether tuned laser radiation could (by influencing the temperature or radical concentrations) be used for improved control of combustion phenomena, for example in damping of oscillatory behavior or in enhancing ignition or flame stabilization in difficult flows (e.g., supersonic combustion). Finally, we note the need for fundamental studies of radiative absorption coefficients at very high intensity levels, in high temperature gases, where non-linear absorption phenomena will become important. We believe our laboratory facilities and past experience with laser diagnostics and chemical kinetics provide unique prospects for research in this general area of laser interactions.

Our thinking on laser interactions with plasmas, for either production or perturbation of a plasma, is further along. Based on a review of current literature, we believe that the generation of plasmas using resonant laser excitation may provide a new and efficient method for creating, maintaining and heating plasmas. A schematic diagram highlighting this idea and its attributes is shown in Fig. 1. The method also provides a means of studying fundamental microscopic collisional and radiative processes involved in plasma production and needed in modeling plasma behavior in a wide range of applications. Our literature review suggests that limited experimental work has been devoted to the study of this new class of dense plasma production which provides, for example, extremely rapid heating rates. The fast changes in free electron temperature achievable create the possibility of providing an intense source of high frequency (short wavelength) radiation. Additionally, the superelastic laser energy conversion has several potential advantages over inverse bremsstrahlung interactions as a means for coupling laser energy into a plasma.

Our plan is to design experiments which will identify and quantify important collisional and radiative interactions present when a gaseous medium is subjected to a sudden pulse of intense laser radiation tuned to the resonance transition of an atomic species. Precise monitoring of

PLASMA GENERATION BY RESONANCE LASER EXCITATION

- Intense pulses of resonance laser radiation provide a new, efficient method for creating, maintaining and heating plasmas



ENERGY LEVEL DIAGRAM OF
IONIZATION PROCESS

- Superelastic laser energy conversion presents several advantages over inverse bremsstrahlung plasma heating
- Extremely rapid plasma heating is relevant to development of x-ray lasers
- Resonance excitation is well suited for studies of fundamental microscopic collisional and radiative processes in plasmas
- Technique relevant to production of plasma guid channels, needed to transport charged particle beams in future particle-beam fusion reactors

Fig. 1. Overview of concept of plasma excitation using resonance laser radiation.

the time-dependent behavior of the bound states of the atom, beginning with the saturation in the lower levels and extending through ionization burn out, will provide an understanding of the fundamental physical processes taking place in these laser-excited plasmas. Species of interest will be atomic sodium, argon or hydrogen, heated in a static cell, or in a flowing system using either microwave heating or our induction-heated plasma torch. Laser sources will include a tunable pulsed dye laser for excitation and both a tunable cw and pulsed dye laser for fluorescence-based detection of the atomic states and plasma parameters.

We believe that fundamental experiments of this type offer potential not only for basic research on laser-plasma dynamics but also for possible applications of lasers for selective nonequilibrium plasma control in future energy conversion schemes.

Publications and Presentations

None

Personnel

Ronald K. Hanson	Professor, Mechanical Engineering
Jerry Seitzman	Graduate Student, Mechanical Engineering (Ph.D. expected in June 1987

2.7 New Techniques and Topics

The major goal of the Stanford Program has been the innovation of modern laser-based diagnostic techniques appropriate for the characterization of reacting flows and plasmas. This program is viewed as a multi-year effort, and as such we focus a portion of our effort each year on the preliminary investigation of new techniques. New ideas receiving attention during the past year have included: (1) 2-d visualization (imaging) of pressure and vorticity; (2) 2-d visualization of CO, H and O concentrations using two-photon fluorescence; (3) laser-excited chemistry of high temperature gases and plasmas; (4) laser energy transfer in high temperature gases and plasmas by linear and non-linear absorption; and (5) new approaches for instantaneous recording of particle sizes in a plane (2-d particle sizing by intensity). The more promising of these activities have been incorporated into our current research or will form the basis for new research to be included in our next proposal.

Areas in which we are currently considering exploratory research include the following: (1) digital and optical processing of 2-d (and 3-d) visualization data sets; (2) alternatives to PLIF for plasma diagnostics, such as polarization-sensitive phenomena; (3) further study of non-linear, multi-photon approaches for PLIF imaging; (4) laser-surface interactions; (5) PLIF strategies for new species, such as fuel vapor, CO_2 and H_2O; and (6) diagnostics needs for supersonic combustion.

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